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APPLICATION OF EMULSIFIED FUELS TO DIESEL AND BOILER PLANT

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APPLICATION OF EMULSIFIED FUELS TO DIESEL AND BOILER PLANT

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SYNOPSIS

Recent events have emphasized the need for mankind to maximize the benefits to be gained from limited energy resources with an urgent requirements to rationalize the use of, and hence conserve, expedient liquid fossil fuels. Concurrently, specific Governments have, under ecological pressure, ruled that emissions from internal combustion engines should be minimized and confined to well defined legally enforcable limits. These two stringent requirements have kindled a re-interest in combustion technology with particular emphasis on the Internal Combustion Engine's operational capabilities. Two critical paths occur: a) to redesign the engine either in part or toto: or b) to modify the combustion characteristics of the fuel. Of these two the former indicates long term and relatively expensive development often involving radical departures i.e. Rankine and Stirling Cycle utilization or in the simplest case the improvement of atomization and distribution by the utilization of high pressure injection techniques, enforced vortex swirl, exhaust gas recirculation etc. In each case additional complexity results in a questionable compromize in terms of fuel economy, power to weight ratio, emission control, reliability and maintenance. There is, therefore, a considerable level of interest, particularly at corporate and Government level, in evaluating fuel additives which will achieve, in some measure and at viable cost, the objectives indicated above. The most popular suggestion to date has been the introduction of water to the combustion space leading to the "development" of several systems each with its own series of claims regarding application and results. Often the results have been over emphasized and claims for improvement over enthusiastic, and consequently this particular field of endeavour has been met with considerable scepticism by potential users and developers alike – an unfortunate circumstance. The prime objective of this paper is to provide a relatively brief precis of the effort applied to date with specific emphasis on results obtained from quantitative experiments undertaken at the University of Newcastle upon Tyne or under its control. Also an extensive bibliography is included at the rear for those who have an insatiable desire for additional persecution.

ABBREVIATIONS

BTDC	Before top dead centre
CR	Compression ratio
DSN	Dunedin Smoke Number
HC	Hydrocarbon
MCR	Maximum continuous rating
NAPTC	Normal atmospheric pressure and temperature conditions
SFC	Specific fuel consumption

1. SUBJECT SURVEY

Weiss and Rudd(1) report that Benki used water as an internal coolant in combustion engines operating on the Otto cycle prior to 1900 as did Hopkinson(2) in 1913 on the gas engine, thereby eliminating detonation. Tractor engines in the mid 1920's were also commonly fitted with water injection equipment when using hot bulb oil engines. In 1938 Kuhrug(3) published results indicating substantial power gains on a Jaguar MKIV aircraft engine subjected to water injection. Since that era many other researchers have publicised active interest in the field, as indicated under References. No doubt many readers will reminisce on their experience in improving pre-war Bentley performance by introducing water in to the inlet manifold etc.

More recently, i.e. in last five to ten years, research activity in this area has been fragmented but substantial, covering the five general topics:

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1) boilers;
2) petrol Injection Engines;
3) carburetted Petrol Engines;
4) diesels;
5) gas Turbines.

Before evaluating developments in each of these combustion systems it is considered prudent to state the following:

Water may be introduced to combustion space in several different ways:

a) mixture with fuel;
b) water in oil emulsion;
c) oil in water emulsion;
d) separate injection;
e) via inlet manifold;
f) via piston crown.

Each of the above methods and associated derivations have their own advocates although objectivity indicates that in all cases a compromise is involved. It is the authors contention that to achieve the prime function of net fuel and NO_x reduction, the use of method b) without the addition of surfactant is the most attractive. However, it is of interest to review current activities sector by sector before drawing hard lines of demarcation leading to potential disputes.

1.1 *Boilers*

As indicated earlier, information leaked to the popular press often containing exagerated claims regarding fuel savings etc., has led to a semi-commercial involvement by various organizations each attempting to produce a device or system capable of satisfying the current requirement of infinite power at zero fuel consumption.

TABLE I

Indentification	Principle of Operation	Performance Claims	Indicated Optimum Water %	Fuel Acceptability	Applicable Range Rate (Type)	Form of Installation	Patents	Manufacturers
Cottell Reactor	Ultrasonic vibrating probe (piezoelectric crystal driven).	Emission control; major energy utilization improvements; coal slurry fuel extension	~ 17%	All	~ 150 gall/hr. (per unit). (B)	Add-on	Yes	Tymponic Corp., U.S.A.
Dynatrol Emulsor	Mechanical cavitation and shear	Fuel economy emission control	Fully modulated to optimize performance	All	Unlimited (D, G.T., B, P.E.)	Add-on	Yes	Tedco Products London, U.K.
ELF Multi-fluid burner	Air-water-fuel co-injection	Particulate control; sludge or waste liquid; gas incineration.	20 to 30%	All	3 to 500 tons per day or 5 - 500 kg fuel per hr. (B)	Complete burner replacement.	Pending	ELF Unio Paris, France.
LFE Emulsifier	High Shear Mech. variable droplet size.	Undisclosed	Fully modulated 6%*	High distillate	18 x 10^6 Btu./hr. Unlimited (B)	Add-on	Applied for.	Langley Economy Watford, U.K.
MGD (Micro-gas) fuel converter	gas/water/fuel venturi recirculation.	Waste processing; emission control; liquid fuel replacement of natural gas combustion, coal slurry fuel extension.	10 - 20%	No.2**	Unknown	Add-on	Yes	SMS Asso USA
TOTAL Emulsifier	Ultrasonic vibrating disc (pressure driven)	Particulate & thermal NO_x control	~ 20%	All***	~ 325 gall/hr.	Add-on	Yes	Companie Francais de Raffi Paris France.

* Subject to further research ** Requires ~ 600 ppm surfactant *** Requires 2% surfactant addition for No.2 oil

Legend:

D	Diesel	P.E.	Petrol Engines
G.T.	Gas Turbine	B	Boilers

And in the case of b) or c) with or without an additive used to promote the emulsification process. Methods a), d) and f) could have additives included to improve combustion or increase the calorific value of the "fuel".

Table I summarizes those units currently known to be either commercially available or in an advanced prototype condition suitable for incorporation on low pressure combustion systems. The claims made are, in the main, those stipulated by the developers although it is logical to assume that significant fuel savings as opposed to reduced maintenance can only be realised on simple systems of low intrinsic design efficiency.

It is interesting to note that with one exception all the systems listed suggest the need for relatively high values of water irrespective of boiler design and function in order to achieve the stipulated objectives.

More serious* research was undertaken by Ivanor and Nefedov(4) of the USSR in the 1960's, indicating that emulsions that burn faster improve the process of combustion and reduce resulting exhaust constituents. They also propounded the micro explosion theory which is currently receiving much attention by academic researchers in the USA (Dryer et al(5)). The prime objective of Ivanor and Nefedov was to determine the differences which would occur between the combustion of emulsified and anhydrous fuels and must, therefore, be considered a preapplication research activity.

Similar experiments were undertaken in the West by Barrett et al(6) at Battelle Columbus Laboratories under the auspices of the currently named Environmental Protection Agency (EPA). Turner and Siezmund(7) in 1973 continued the work a little further to demonstrate that under certain conditions of combustion, emulsions reduce thermal NO_x but not fuel related NO_x.

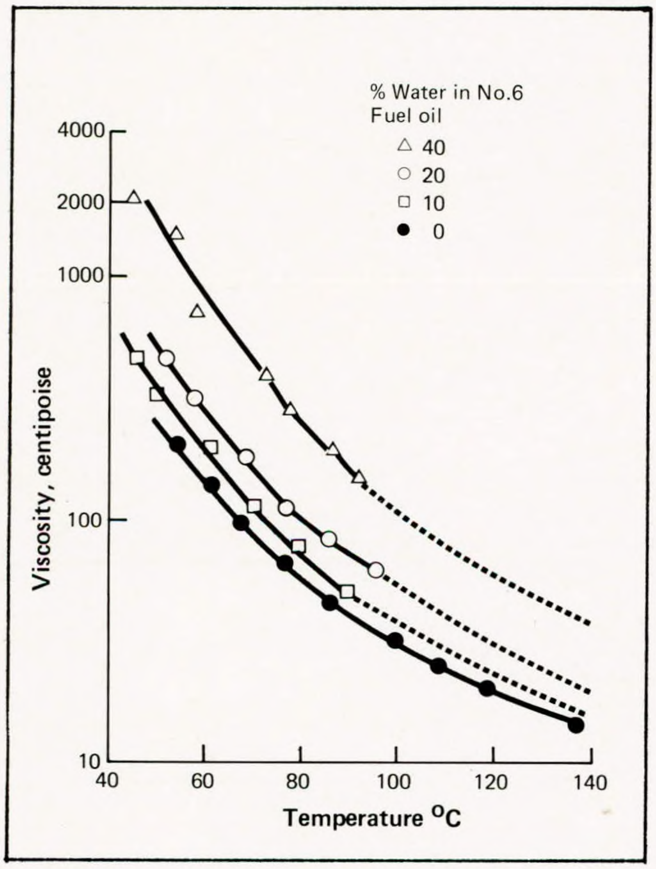


FIG 1 *Emulsion viscosity variation with temperature*

The research of Barrett with particular emphasis on viscosity change (See Fig. 1), was put to good use by Schener and Trainie(8) who reasoned that as viscosity increased with water content more preheat was required prior to injection to maintain similar atomization characteristics. The results of testing five variously sized domestic oil-fired boilers (1.5×10^4 to 2×10^6 Btu/hour) indicated a reduction in participate emissions of at least 10 to 1 i.e. .08 reduced to .008 lb/MBtu. Furthermore, particulates of combustion in excess of 5 microns could be eliminated completely with significant reduction in excess air.

Hall(9) published the results of detailed experiments on a Scotch Boiler burning residual oils (2.5 million Btu/hour, 17 gph fuel rate), obtained by testing two of the devices shown in Table I (Total and Cottell) and proferred the conclusions that combustion was cleaner, i.e. particulates reduced, and under certain conditions that combustion efficiency could be improved by a maximum of 2%. However, no significant effect on NO_x SO_2 or HC was to be noted.

Volkmar et al(10), Kinney and Lombard(11) using emulsifiers and homogenisers respectively, have independently shown that the combustion of water/ fuel mixes on shore based installations result in a reduction of overall operating cost but not necessarily an improvement in combustion efficiency. Reduced maintenance and excess air together with the utilization of poor quality fuels resulting in the improvement. In both cases, doubts remain as to the phase distribution occuring at burner stagnation point.

In summarizing, therefore, it would appear that little emphasis has been placed upon the application of emulsified fuels to boiler systems of significant size although momentum is gathering.

1.2 ***Summary***

It would appear that a review of recent research activity in the application of emulsified fuels to boilers results in:

a) a reduction in particulate emission;
b) reduction in flame length;
c) less frequent maintenance;
d) reduction in excess air requirement;
e) increase in fuel viscosity;
f) arguably an increase in fuel economy;
g) the need for relatively high water concentrations;
h) combustion of less aesthestic fuels.

1.3 ***Internal Combustion Engine Applications***

As indicated previously the introduction of water to internal combustion engines was a well accepted phenomenon as long ago as 1900, highly recommended as a means of reducing ignition knock and mean temperature generated within the combustion chamber. Further intensive use was made of water fuel alcohol mixtures just prior to and during World War II – the alcohol being introduced to reduce the possibility of water freezing during harsh weather. Primary use was to obtain a "supercharging" effect at take off on aircraft – viz. the Jaguar Mk.IV showed an increase of 21% at take off with no measured deterioration in fuel consumption. In this particular situation water was injected into the air fuel mixture before entry to the supercharger.

Subsequent activity in this area was at most minimal, peacetime operation removing the "scrambling" requirement of aircraft and leading to engines of higher efficiency with a more even distribution of thermal and pressure induced load being developed. The possibility that water could be accidentally introduced to the fuel tank also led to the concept being relegated to the shelves of history.

During the late 60's interest was once again kindled by individual researchers particularly in Germany (12) and although of academic interest the result was not actively pursued by engine designers due to lack of economic

* i.e. activities undertaken to obtain more understanding of the phenomenon involved as opposed to commercial applications.

stimulus. The energy crisis of this decade has modified that situation somewhat.

Weiss and Rudd (13) published comprehensive data resulting from adding mixtures of water and alcohol via the inlet manifold to a single cylinder variable compression Ricardo engine and also a commercial low bhp 4 cylinder 4 stroke engine.

The ratio of water to fuel was varied from 0 to 50% by weight. The results of the tests suggested that a greater flexibility in engine design could be realised by including water in the combustion cycle. For example, compression ratio could be raised from 7 to 9 to 1 and the ignition could be advanced, which in conjunction with a higher octane fuel, produced an improvement in power output (13%) fuel consumption (2 to 7%) and engine cleanliness. The most significant comment resulting from the programme suggested that fuel/water ratio should be varied with speed and load (30% at low power and 4% at maximum). Unfortunately, and expectedly the introduction of water in this way results in condensation on cylinder walls with all the encumbent disadvantages thereof.

Zeilinger (14) in his classic paper of 1971 described the work involved and the results obtained from burning surfactant stabilized emulsions in a petrol injection engine. (86.8 Bmep at 2300 rev/min). Although the author concentrated on the control of Nitrous Oxides and general pollution control, implicit in his results are significant increases

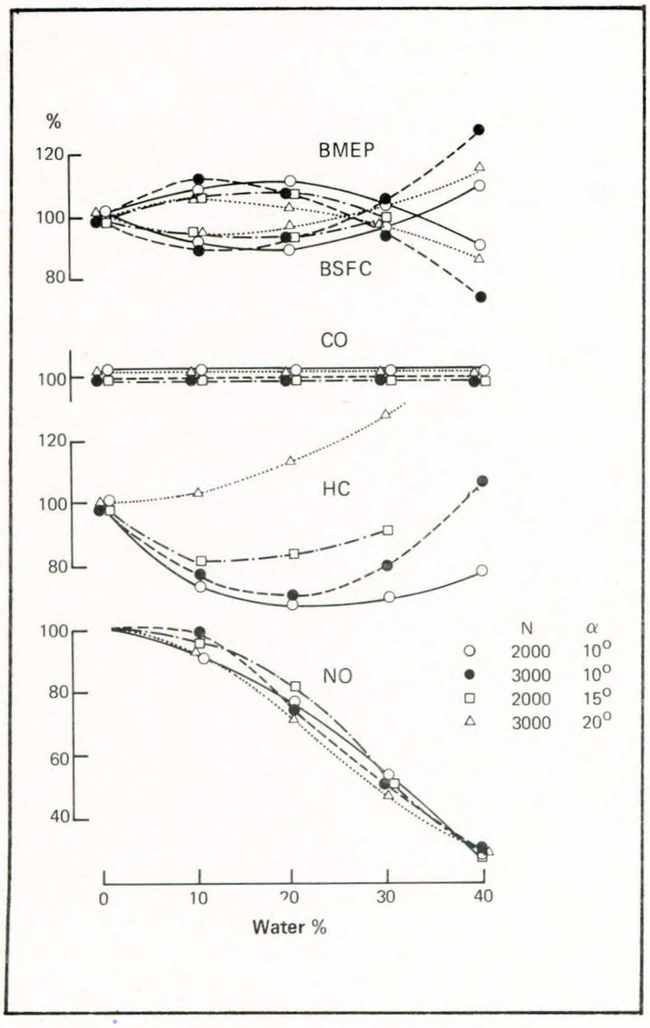


FIG 2 *Typical petrol engine combustion data*

in power output and fuel economy with optima occurring at a 15% water in oil ratio. See Fig. 2, which summarizes results at constant spark timing (21° BTDC) and equivalence ratio ($\emptyset = 1$). Significantly, IMEP was shown to be increased throughout most of the operating range and indicated that equivalence ratio could be reduced below unity to advantage when burning emulsions (Fig. 3). NO_x could be reduced by 55% at water inclusions of 28% with no significant deterioration of SFC. Temperature rise within the combustion process exhibited significant delay with a marginal reduction in absolute value – these are, however, subject to scrutiny as they were calculated by computer programme based upon pressure/time measurements, as too, were the heat release diagrams.

Greeves et al (15) investigated the comparative advantages of introducing water:

a) via the inlet manifold;
b) separate direct water injection system;
c) direct injection as dispersion in fuel;

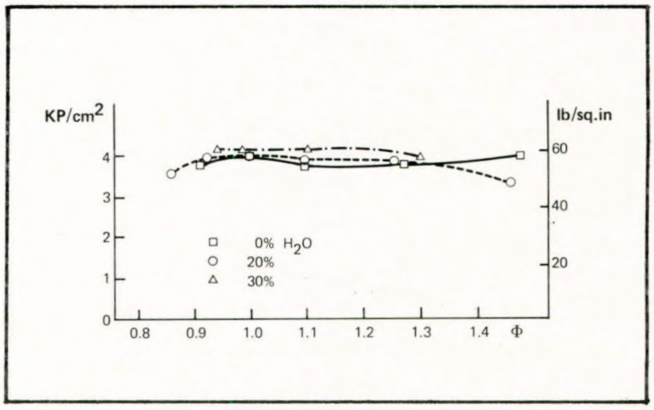


FIG 3 *I.M.E.P. as function of the equivalence ratio Φ for different water quantities*

on an automotive diesel engine. Although the researchers concentrated on exhaust pollution control and concluded that NO_x decreases significantly with water inclusion using any of the three methods detailed, the latter, i.e. water/fuel premix injection showed the additional advantage of reduced tendency to smoke and a small increase in SFC at certain loads and ratios. It should be noted that the injection period increased with water fuel ratio due to the fuel system used. Usually, such an increase results in an increase in smoke and CO production; significantly with water included the reverse tendency was shown. An innovation was the capture of spray from the nozzle system in liquid nitrogen for subsequent analysis of droplet size and constituent build, from which the authors concluded that little water was actually contained within the fuel oil globules. This could reasonably be expected as the fuel was a "mix" and not an emulsion.

Murayama et al (16) concentrated on producing a surfactant generated stable emulsion (precipitation 5% per week) but also compared the results of introducing free water in the inlet manifold of a single cylinder marine diesel engine (CR 17.4, 110 mm bore, 150 mm stroke, 1200 rev/min).

The former method of operation showed significant advantages over the latter, NO_x being reduced by the use of both techniques but was more significant with emulsion as too was the improvement in SFC, smoke density and CO concentration; HC concentration, however, was increased.

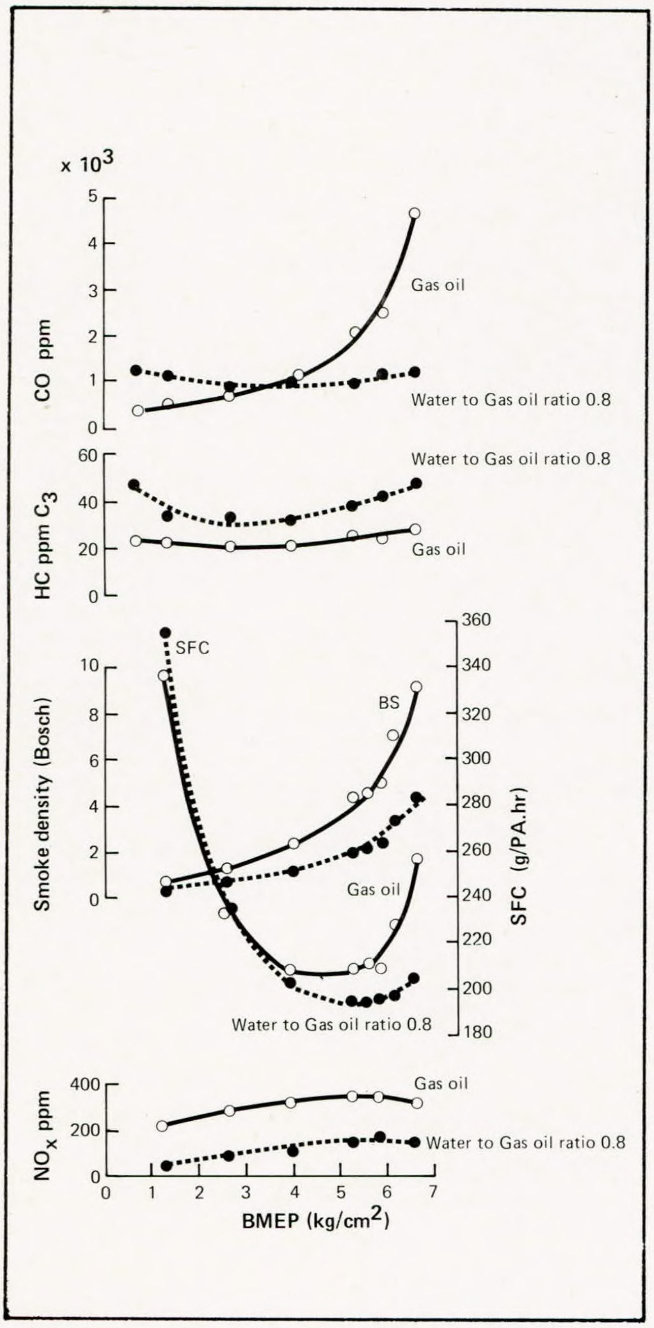


FIG 4 *Engine performance under varied load and retarded injection timing*

The onset of ignition was delayed, peak pressure and rate of heat released increased using emulsified fuel. Significantly, when operating the engine at a retarded ignition condition (11.3° BTDC) emulsified fuel produced large improvements over neat fuel at heavy loads (Fig. 4), but showed a small increase in SFC at low loads.

The above summarizes the efforts of a few researchers in the field; however, further references are included at the end of the paper.

Summarizing the work to date, therefore, it would appear that equivalence ratio, timing, quality of emulsion, engine type, speed and load all have a significant part to play in producing benefits or otherwise in Internal Combustion engines. Engine design efficiency is obviously significant; however, there is sufficient evidence available from diverse sources to indicate that the investigation of emulsified fuels as a means of improving combustion efficiency is worthy of further endeavour.

1.4 *Gas Turbines*

Three fundamental approaches have been made to the design and operation of Gas Turbine fuel systems on water in fuel dispersions to.

a) reduce exhaust smoke;
b) improve combustion efficiency;
c) produce contaminate free blended fuels.

In 1977 Moses (17) indicated that substantial smoke reduction was possible by burning surfactant stabilized emulsions in a burner rig designed specifically for operation on an Allison T63 gas turbine system.

Water to fuel ratios up to and including 50% were burned in the single can combustor having a dual orifice pressure atomizer, resulting in a maximum reduction of exhaust particulate concentration of some 80%. Reference to Figs. 5 and 6 indicate that smoke reduction was obtained at all strengths of emulsion, increasing with percentage of water concentration involved. Significantly, the reduction in combustion efficiency measured at maximum power at water concentrations up to and including 30% were marginal although smoke number was reduced from 28 to 8. The loss in combustion efficiency was shown to increase with decrease in power output. Surfactant concentration of some 2% was shown to be optimum although physical dimensions of the droplet dispersion apparently showed no measurable effect upon performance.

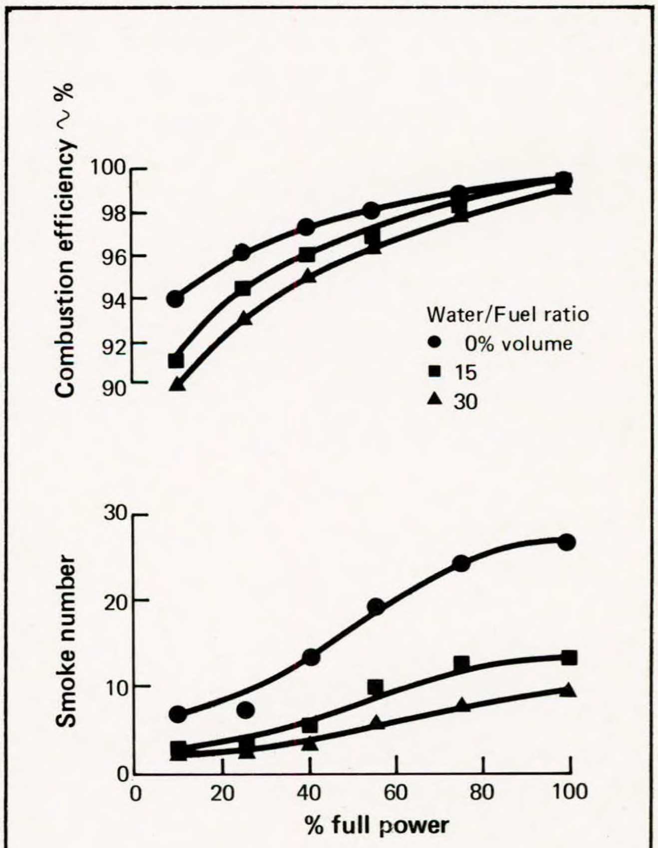


FIG 5 *Summary of the effect of water concentration on smoke number and combustion efficiency over the engine power spectrum*

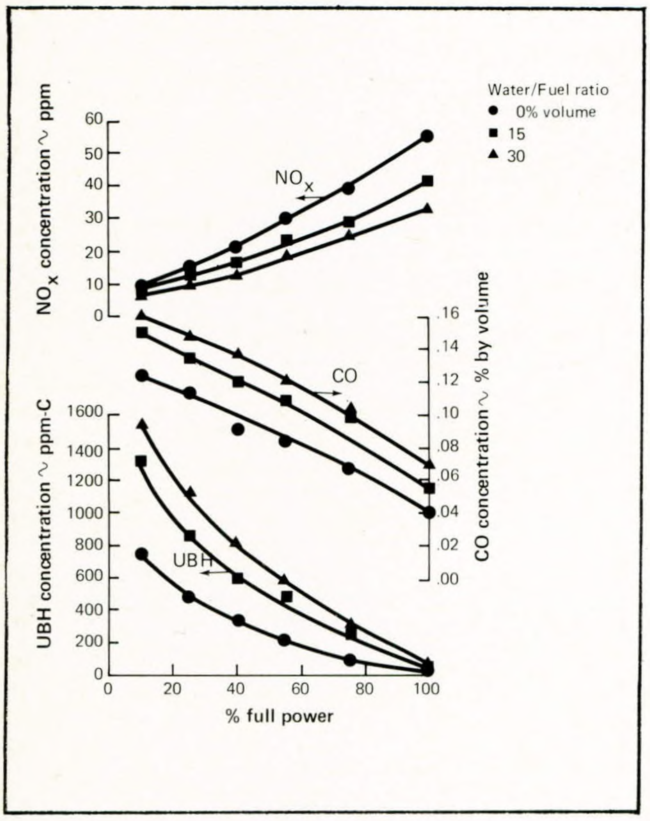


FIG 6 *Summary of the effect of water concentration on the exhaust emissions over the engine power spectrum*

The author concludes that maximum particulate emission occurs at maximum power and in consequence the introduction of emulsified fuel (JP5) at this condition could prove of consequence and he is, therefore, utilizing the experience gained by attempting full scale engine tests on a J79 engine at NAPTC.

Experiments attempted at United Technologies Research Center (Spadaccini, and Pelmas)(18) concentrated on burning, in a simulated FT4 burner can, dispersions of water in residual oil, the continuous phase having viscosities ranging from 5.3 to 200 cs at 310K (Nos. 2, 6 and Redwood 650), the prime objective being to determine the capacity of the water to improve spray dispersion and combustion efficiency by involving the micro explosion phenomenon.

Photomicrographic analysis indicated a water droplet size range of 1 to 5 microns, variation in viscosity and "pourability" were imperceptible in No. 6 oil at concentrations up to 20% by weight; a 50% ratio showed a marked increase in viscosity suggesting, in turn, a higher degree of preheat requirement. Stability was achieved by in line homogenization in all fuels with the exception of No. 2 which required the inclusion of surfactants.

Comparison of results obtained between using pressure atomizing and air boost nozzles showed significant advantages, in terms of combustion efficiency improvement, in the use of the former. As shown in Figs. 7 & 8 concentration ratios of approximately 5% water in oil provide the optimum return for investment. The prime advantage of using the air boost nozzle was thought to be in its apparent ability to reduce the build up of carbon deposits on the nozzle tips.

Probably, the most practical application of emulsified fuels in the gas turbine field has been the "Sea Train" experiment, (Nealis and O'Neil (19)) where blended residual oils have been used to advantage although not without some embryo difficulties. By using 75% Bunker 'C' homogenized with dirty distillate the vessel *Asia-liner* using two 30 000 hp FT4 gas turbines has logged some 3500 hours of trial operation with an anticipated reduction in fuel cost approaching 23%. Essentially, the fuel treatment system consists of a series of water washing filtration and heating control circuits using additives to remove contaminants in the fuel. Homogenizers are used to reduce the remaining heavy viscosity concentrations to produce a fuel of constant viscosity and pour characteristics. However, even

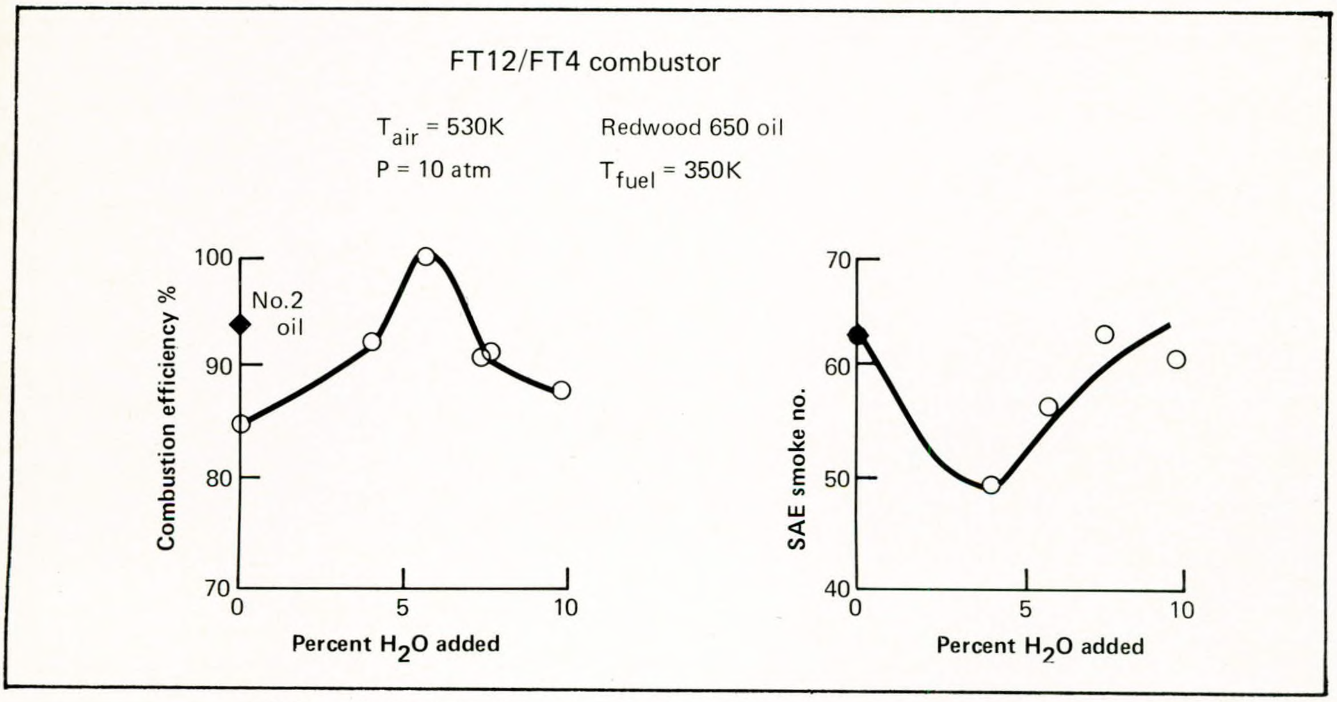


FIG 7 *Combustion efficiency and smoke emissions – pressure-atomizing nozzle*

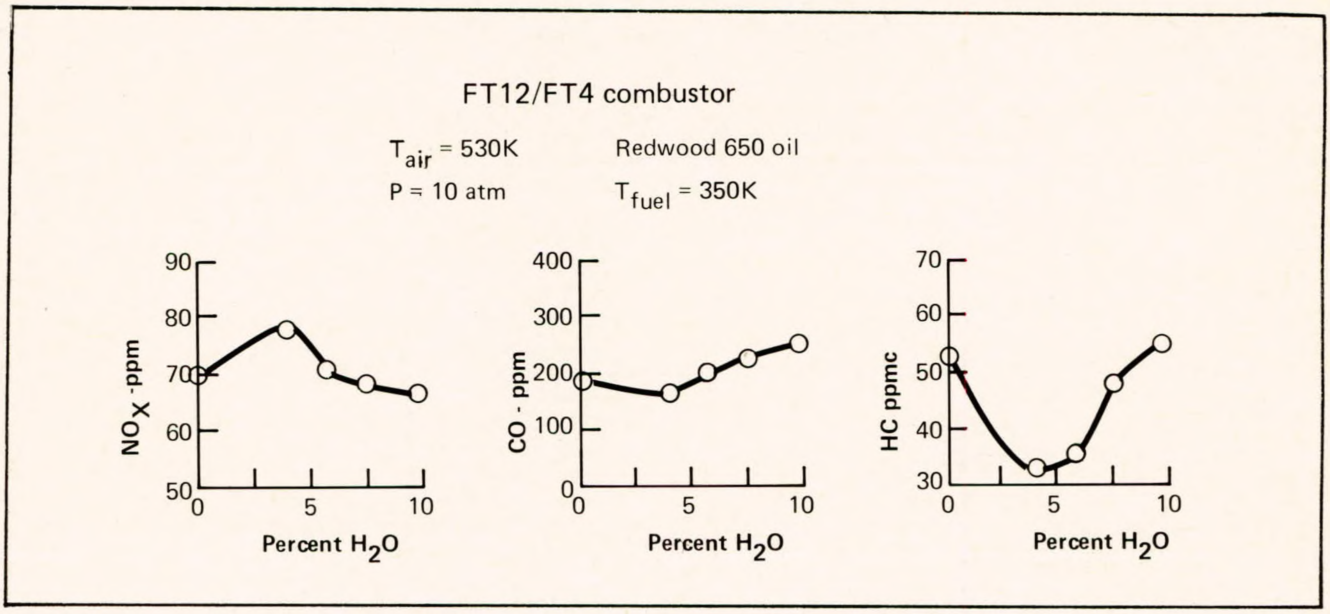


FIG 8 *Gaseous emissions – pressure-atomizing nozzle*

when heated to 220°F heavy oils will have a droplet size, when exhausting via the fuel nozzles, approaching 120 micron which results in a substantial combustion delay incompatible with burner can dimensions.

The addition of water of concentration 5-10% by weight immediately prior to final homogenization results in water/oil droplets of a size approaching 20-30 microns which, when mixed with hot gases in the can, micro explode causing a further reduction in particle size with an equitable enhancement in combustion rate.

The intial anticipated additional maintenance cost was assumed to be approximately \$2 per ton of fuel oil burned but, in reality, after teething difficulties, engine inspection at 3000 hours indicated no component or hot section deterioration.

The Company are currently re-equipping the fleet of 4 container ships which are expected to log 6000 hours/engine/year at 85% rated power (23 000 bhp) at average speeds of 23 knots. Fuel rate is expected to increase over high distillate due to heating the water (1%) and lower calorific of the fuel (3%) but overall costs should maintain a 20% advantage.

2. UNIVERSITY RELATED RESEARCH BOILER ACTIVITIES

Some years ago, staff of the University of Newcastle upon Tyne, by virtue of comments in the popular press etc., generated an interest in emulsified fuels, to the extent of undertaking preliminary experimental investigations on a domestic boiler. At first the results tended to be inconclusive with data being grossly unpredictable. However, there were several data points which indicated a significant, if random, saving in fuel consumption or improvement in combustion efficiency.

The process involved, consisted of mixing "emulsions", using a range of devices with and without additives, on a continuous basis immediately prior to the pump inlet (pressure jet burner system). Smoke number was measured when stack temperature stabilized and air damper control modified to achieve a specific value of smoke number; CO_2 and temperature being compared between pure fuel and emulsion, from which data relative combustion efficiency could be derived.

In the majority of cases fuel consumption per exothermic unit of heat generated increased, however, under apparently indefinable situations combustion efficiency improved as recorded by a marked increase in measured CO_2.

Further, often exasperating, experiments indicated the following tendencies.

Fuel oil plus surfactant only produced a reduction in CO_2 content in comparison with fuel oil only. The subsequent addition of H_2O restored the situation but, in terms of heat produced no further improvements.

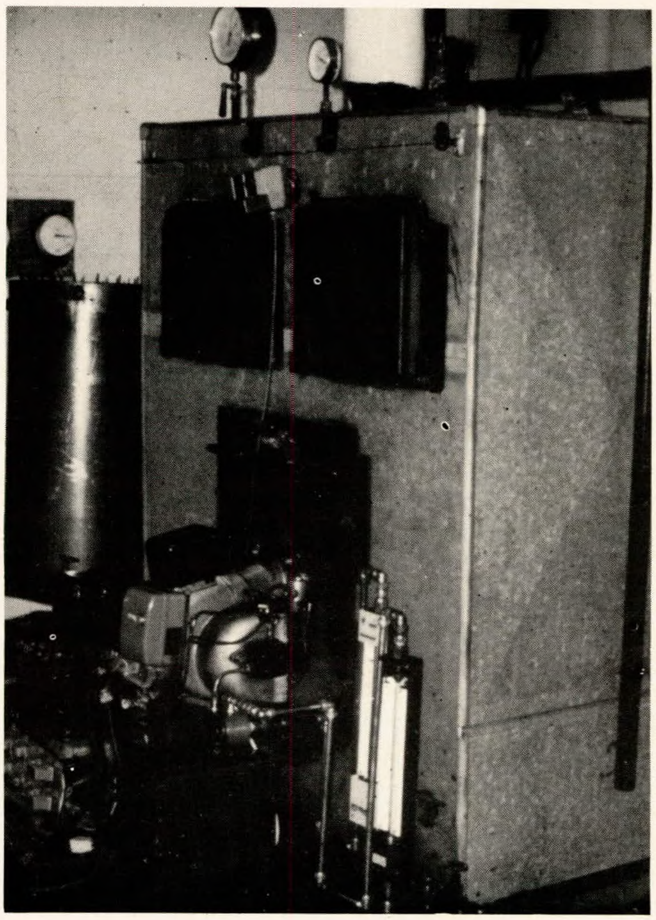


FIG 9 *Initial boiler test facility*

Fuel/H_2O mixes produced an improvement in optimum CO_2 output only in the case of water in oil emulsion at particular ratios. Oil in water emulsions and homogenous mixes generally reduced the combustion efficiency. A dye technique was used to determine the form of the solution as normal visual methods could not distinguish any variation – all types having a pink milky appearance.

The problem at that stage, therefore, was to produce a water in oil emulsion on a predictable and continuous basis without the use of surfactant additives (for obvious commercial and technical reasons).

Theoretical aspects of emulsion production were researched leading, ultimately, to a semi empirical solution obtained over a considerable period involving a mechanical device using the combined effects of cavitation and shear to create the designed product.

Flushed with success further tests were undertaken on a larger boiler system, 1.5 x 10^6 Btu/hour operating with a similar pressure jet burner facility (Fig. 9). A significant advantage of the selected system was the opportunity it afforded of flame accessibility. Brief details of the boiler used and modifications made follow.

2.1 *Initial Boiler Trials*

The boiler, being a small industrial heating unit, operated on 35 sec. oil supplied under gravity to a gear pump which produced 120 psi at nozzle stagnation chamber. The normal load comprised an 'on-off' duty cycle at a fixed firing rate.

The water required for combustion purposes was supplied from the mains via a header tank, manual controlled metering value, non return valve and an electrically controlled solenoid valve to the emulsification device which was, itself, situated immediately before the inlet to the gear pump (within 15 inches).

Initially, a simple sequential control unit was designed and integrated with the existing burner "light-up - shut down" control unit to provide the following facility:

1) check solenoid valve closed;
2) ignition circuit energised;
3) electric motor accelerated;
4) check fuel ignition (photocell system);
5) activate emulsifier drive motor;
6) open solenoid;
7) check combustion on emulsified fuel.

The delay time included between steps 4 and 5 or 5 and 6 could be modified to a maximum of 30 seconds.

On shut down the process was almost reversed except that the emulsifier was switched off coincident with pump motor, the solenoid valve being closed some 10 seconds before, i.e. upon receipt of thermostat signal.

The above system ensured that:

a) mains water was not contaminated by backflow of oil;
b) light up and shut down was accomplished on fuel oil only.

All the normal safety controls, i.e. flame failure, pre-ignition purge etc., were unaffected and continued to operate normally.

2.1.1 *Initial Test Results*

Subsequent to the necessary familiarization tests the system was operated over a range of water/fuel mixes varied from 0 to 65% by volume.

Initially, the most significant result, following an increase in confidence, was the fundamental effect which the addition of water had on flame configuration. Invariably, a considerable increase in length and surface area would be demonstrated as water was added. This occurred to such a degree that smaller nozzles were required in the facility to overcome the effect of severe flame impingement on boiler back plate. As an example of this phenomenon, the flame extended approximated 50% at a water concentration of 35%.

When operating on pure fuel oil there was no perceptable variation in combustion efficiency between either set of nozzles and consequently the results may be considered of some credence.

Table II provides an indication of the change in combustion efficiency resulting from the trials. It should be noted that an increase in pump pressure was a necessary requirement to meet the replacement nozzle performance criteria.

With respect to visual changes Figs. 10 to 15 show the effect of water content on flame characteristics.

In the pure fuel condition small globules of oil created by the atomization process manage to avoid combustion and are transported around the periphery of the flame through the flue. As the water content is increased these globules are "captured" and burned causing the 'sparklet" effect shown. (Figs. 10/15). The further addition of water tends to accentuate this phenomenon which is accompanied by an increase in flame irregularity.

At a disproportionate water content (an emotive statement), 55-65% combustion reaches the limit of stability, the flame becoming detached and of random character. The blue spectre involved is synonymous with the conversion of CO to CO_2 and a visual result of the reduction in combustion rate.

TABLE II 1.5 x 10^6 BOILER DATA

	Exhaust Temp. ^oF	CO_2 %	Bach. Smoke Number	Oil Flow Rate Gal/min	H_2O Flow Rate Gal/Min	Combustion Efficiency %
Pure Fuel Oil	740	8.5	3	0.182	0	70.5
5.4% H_2O	700	10	3	0.174	0.01	74.5
13.4% H_2O	660	11	3	0.160	0.024	77.5

FIG 10

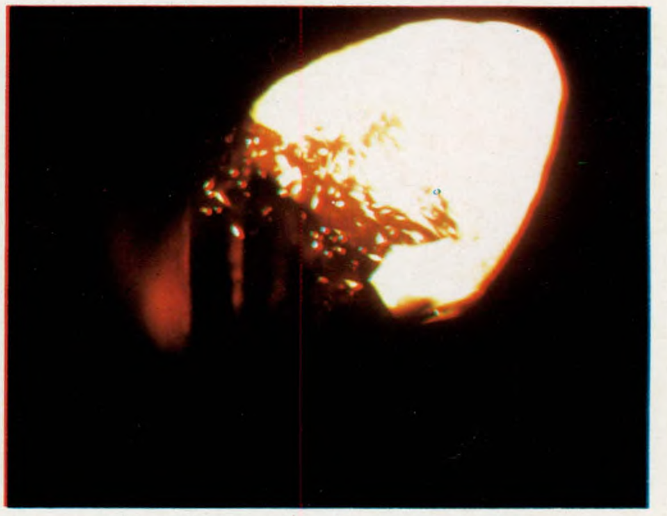


FIG 11

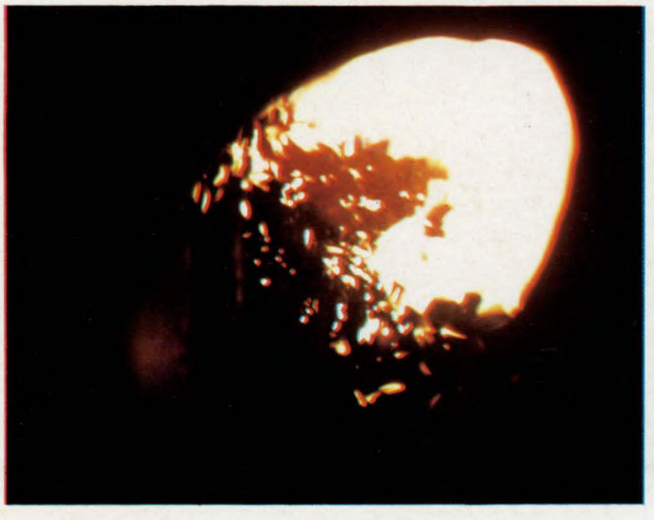


FIG 12

FIG 13

FIG 14

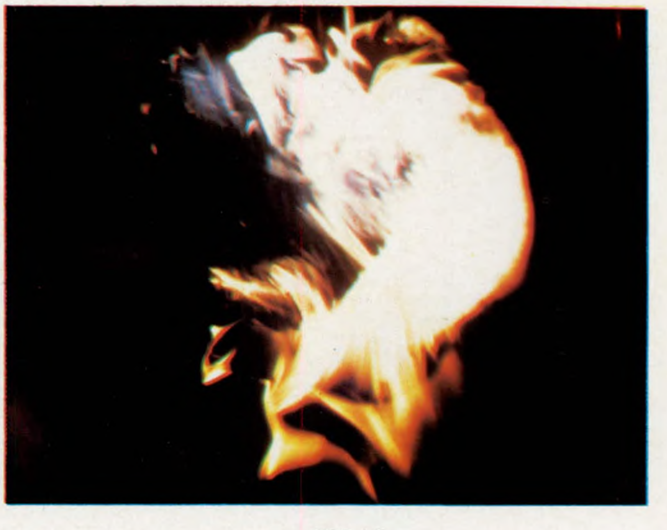


FIG 15

FIG 10 *0% H_2O optimum flame*
FIGS 11-14 *Increasing percentage of H_2O*
FIG 15 *65% H_2O. Limit of flame stability*

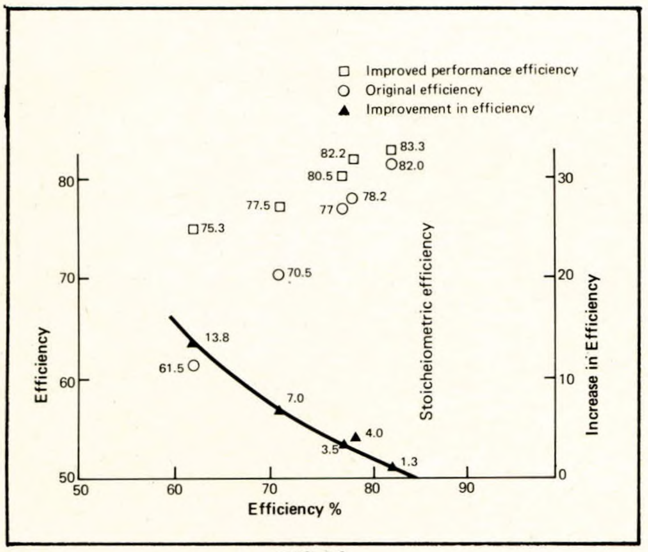


FIG 16

Figure 16 shows the result of applying emulsified fuel technology to five different boilers using the process indicated above, i.e. tuning for maximum efficiency on oil prior to the determination of the effect of emulsified fuel on combustion.

A clinical assessment of the results indicates that a relatively inefficient pressure jet boiler may have its combustion characteristics considerably improved by the application of emulsified fuels to the burner. As the base operating efficiency increases the scope for improvement decreases and hence the benefits to be gained from emulsified fuel utilization are reduced accordingly.

The boilers involved in Figure 16 are a relatively simple type used to satisfy industrial heating requirements having a stoiciometric efficiency of approximately 84% and hence those examined represent a cross-section of units ranging from relatively inefficient to extremely good.

Apart from combustion efficiency certain other benefits were evident from the results of the tests.

Combustion was extremely clean – removing the cleaning maintenance requirement almost entirely – start up on emulsion was straightforward removing the necessity for sequential control schemes and flame geometric variation increased heat transfer capacity of each unit and increased flexibility in boiler/burner design.

To illustrate the point the 1.8 x 10^{-6} Btu/h. boiler had not been cleaned over a period of three years when operating on emulsified fuels and a CO_2 production plant has had its cleaning schedule increased from 48 hours to 30 days on an experimental basis. The latter project being an ongoing programme.

3. PRELIMINARY DIESEL TRIALS

Having demonstrated, albeit in a visual rather than totally scientific sense, that water could be introduced to a combustion space to some advantage, attention naturally turned to the diesel engine.

A simple system was engineered and a quantity of emulsion produced and introduced to a complementary range of engines, namely: a single cylinder, medium speed research engine, a single cylinder Gardiner engine and a multicylinder industrial engine.

Class A fuel was used on all the engines although a further series of tests were completed using 950 sec. fuel on the multicylinder engine.

At a later stage a prototype "on engine" system was developed and used on high speed engines burning standard derv.

Typical results and observations are listed below.

3.1 *Single Cylinder Medium Speed Engine*

3.1.1 *Engine*

The engine involved in the test procedure was a four stroke direct injection diesel engine pressure charged by means of an indendently driven blower.

Engine parameters were as follows:

Bore (mm)	203
Stroke (mm)	273
Piston displacement (cc)	8876
Piston speed (m/sec.)	9.14
B.m.e.p. (bars)	16.9
Compression pressure (bars)	72.4
Compression ratio	12.2 : 1
Design firing pressure (bars)	120.5
Injection pressure (bars)	222

3.1.2 *Experimental Data*

The engine was supplied with several emulsions ranging from 15 to 25% by volume of water and the results compared with base line data obtained on fuel oil only.

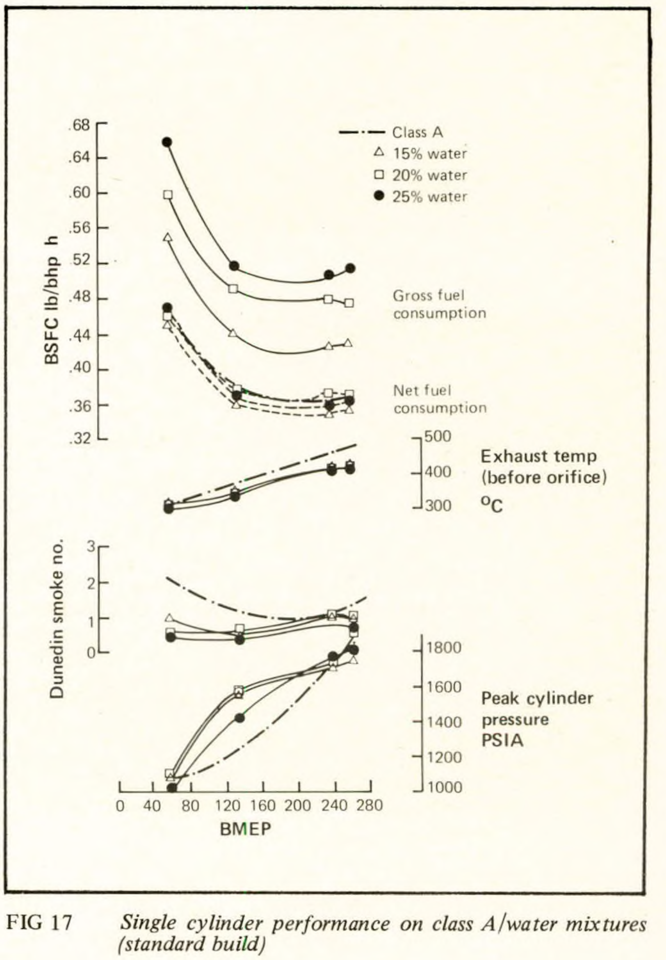


FIG 17 *Single cylinder performance on class A/water mixtures (standard build)*

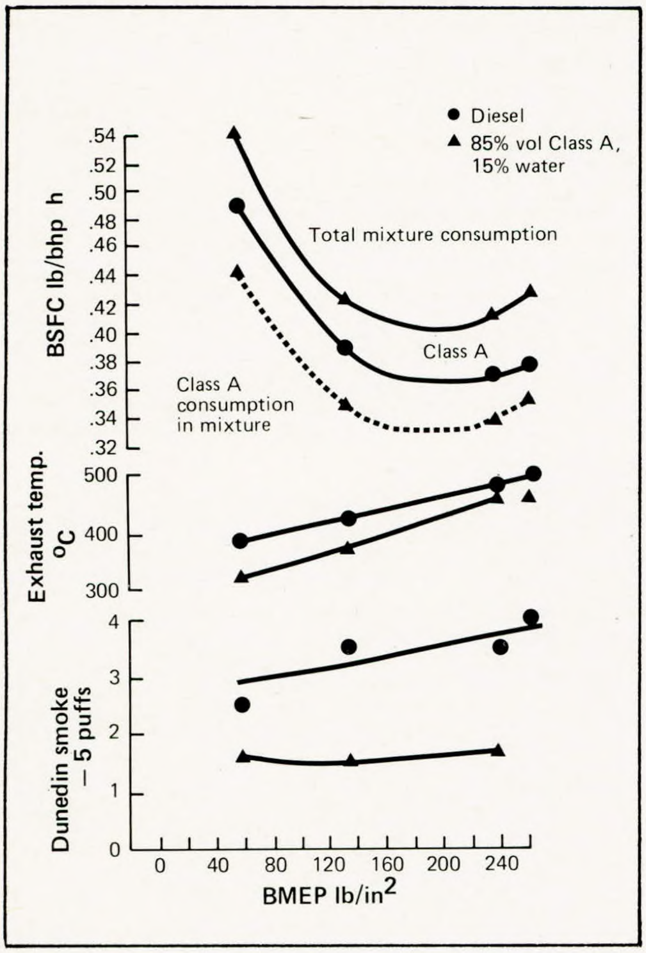


FIG 18 *Comparison of performance single cylinder 1000 RPM (Deep Hesselman Crown Piston)*

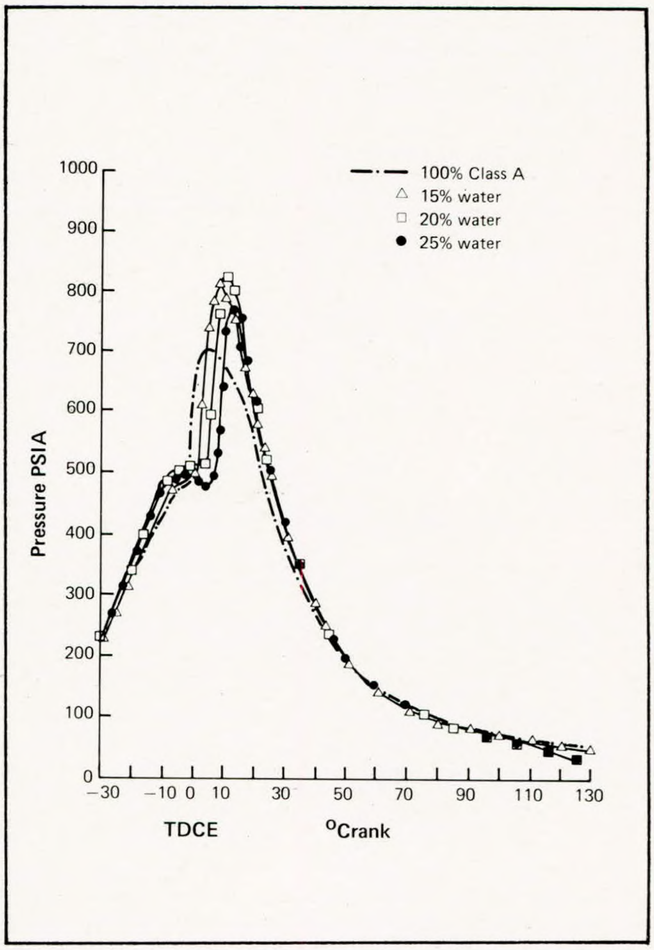


FIG 19 *Single cylinder 60 lbf/in² 1000 RPM cylinder pressures water/fuel mixtures*

The complete load range was covered at a constant rev/min of 1000. Some further tests were completed on the engine when fitted with a piston of the deep bowl Hesselman type.

In all cases the engine was thoroughly warmed on "pure" Class "A" fuel, usually at high load factors, prior to the imposition of an emulsified product, whereupon data were determined over a range of imposed loads. In an attempt to minimize errors the Class "A" datum values were checked once again at the completion of operation on emulsified fuel.

3.1.3 *Typical Results*

Figures 17 and 18 show the standard build and Hesselman crown results respectively.

It may be seen that the net fuel consumption of Class "A" fuel was apparently improved to some extent at all water concentrations tested when operating at the low and part load condition.

At full load the 15% mixture suggested an improvement of some 4.4% over base line data to an estimated specific fuel consumption of 0.349 lb/bhp/h. Any improvement at the 25% value may be considered to be marginal with 20% water in oil operation exhibiting a distinct increase in net fuel consumption.

The results indicate that exhaust temperatures were, to some extent, independent of the quantity of water included in the fuel, certainly within the test range recorded, showing a reduction averaging 35°C at full load over the normal operating condition.

Exhaust smoke improvement was visually most marked at low loads, subsequent smokemeter readings indicating an improvement throughout the load range, although this was quite small at the full power condition.

Of particular interest is the fact that peak cylinder pressures at full load showed no perceptible variation between operation on basic fuel or emulsion, although at part load a significant increase is exhibited when burning the latter. Fig. 19 shows the intermediate load cylinder pressures for the mixtures involved.

The performance on 15% water/fuel with the deep Hesselman crown showed the same trends as with the standard build except that the overall improvements to smoke and fuel consumption were more marked. Over the load range an average improvement of 8.8% in fuel consumption was achieved, at part load the improvement was 10.7%. This compares with an average improvement of 4.4% with the standard build. Exhaust smoke was visibly much improved, particularly at high loads where on Class "A" a smokemeter reading of 3.5 (slightly smoky-smoky) was reduced to 1.7 (clear). At full load cylinder pressures were similar to the datum case, with a delay to the start of combustion in the 20% and 25% cases indicating that the rate of heat release was apparently increased. Figure 20 shows the start of combustion in relation to the start and finish of injection for the mixtures at various loads.

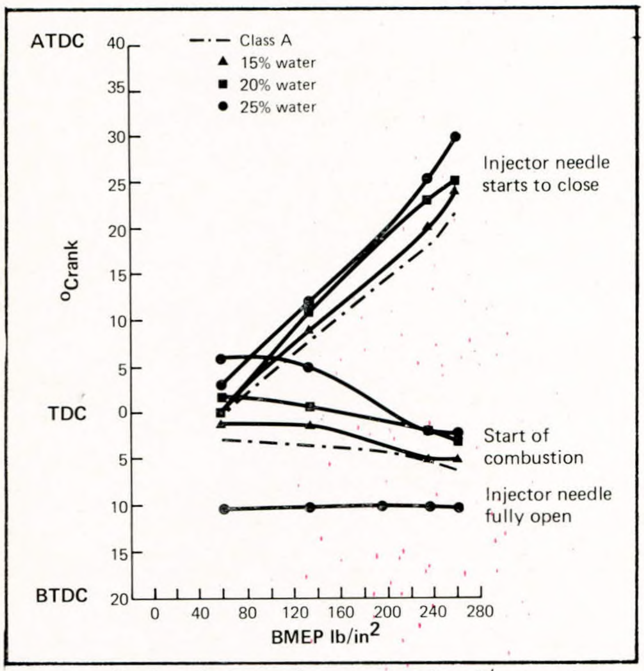


FIG 20 *Single cylinder performance on class A/water mixtures injection events and start of combustion, delay period and injection period*

3.2 *Multi Cylinder Medium Speed Industrial Engines*

3.2.1 *Engine*

The engine made available for test was of the eight cylinder, four stroke direct injection turbo charged variety operating on the following design parameters:

Bore (mm)	317
Stroke (mm)	368
Speed (rev/min)	600
Bmep (bars)	13.8

3.2.2 *Engine Trials*

The experimental procedure involved was similar to that used in the previous programme except that two baseline fuels were used i.e. Class "A" and 950 sec. to be compared with only one level of water in oil emulsion viz 15%.

Table III lists relevant data.

3.2.3 *Results*

The results using Class "A" fuel followed the usual trend of a minor variation in fuel consumption at rated power when comparing pure fuel with a 15% mix, but a measurable improvement (5.4%) at part load. Significantly the heavy fuel (950 sec.) results indicate fuel savings, at both the full and part load commitment, of the order of 4 to 4.5%.

Rated cylinder peak pressures were unchanged when comparing Class "A"/emulsion operation, however a decrease of approximately 60 psi was apparent when using the heavier fuel. Intermediate load peak pressures were measurably increased in both cases, 60 psi and 20 psi on light and heavy fuels respectively.

Exhaust smoke was visibly unchanged both with Class "A" and heavy fuel mixtures at full load, being clear in all cases. The smokemeter reading did show a small improvement to an already low reading. Part load smoke on Class "A" mixture was slightly clearer than on 100% Class "A". Again, smokemeter readings showed small improvements.

Exhaust temperatures were lower on the Class "A" mixture by about 10 to 15°C, measured at the pulse converter entry. On heavy fuel mixture they were reduced on part load only and then by as little as 7°C. Exhaust temperatures are, of course, influenced by turbocharger performance and, in particular, by air flow which was modified in each case, except at part load on Class "A".

TABLE III MULTI-CYLINDER ENGINE TEST RESULTS

Fuel	Class A				Heavy Fuel (950 sec.)			
Fuel in emulsion % by volume	100	.85	100	.85	100	.85	100	.85
Speed	600	600	600	600	600	600	600	600
Load (Bmep) (psi)	204	204	100	100	204	204	100	100
Fuel (net)	.356	.351	.372	.353	.373	.357	.380	.363
BSFC lb/bhp/h Total (gross)		.426		.432		.422		.430
Peak pressure psi	1620	1622	1094	1156	1685	1625	1125	1142
Exhaust temp. °C	518	503	386	374	488	488	392	385
Boost pressure "Hg"	39.6	38	11.4	12	40	39	11.9	11
Blower speed rev/min	22200	21700	13300	13300	22230	-	13600	-
Visual	C	C	SS	C/SS	C	C	-	C/SS
Exhaust smoke DSN	0.2	0	0.3	0.2	0.3	0.2	0.3	0.2

3.3 *Single Cylinder High Speed Industrial Engine Tests*

3.3.1 *Engine*

The Gardiner engine used was a single cylinder 4.25" bore, 6" stroke engine with a high swirl type direct injection combustion chamber. It was naturally aspirated and gave a maximum of 90 Bmep at 1500 rev/min and was fitted with a Farnboro Cylinder pressure indicator and a chemiluminescent type of exhaust gas analyser to measure NO_x levels.

3.3.2 *Engine Tests*

The test programme covered the load range at 1500 and 750 rev/min with a 15% water concentration. In addition to water/fuel emulsions a lime water (calcium hydroxide solution)/fuel emulsion was tested to study the effect upon exhaust emissions.

3.3.3 *Results*

The results are shown in Figures 21 and 22. At full load, 1500 rev/min a 7% improvement in SFC was obtained. Exhaust temperatures were reduced by about 40°C and the NO_x emission was reduced to 33% of the Class "A" figure. At 750 rev/min the SFC improved by 8% with the lime water emulsion.

3.4 *Perkins Diesel Engine Tests*

3.4.1 *Engine*

The engine used for these tests was a Perkins P4 Power Unit. Design parameters being as follows:

Bore	3.5 in.
Stroke	5.0 in.
Number of Cylinders	4;
Speed	2,000 rev/min
Compression Ratio	16.5 : 1

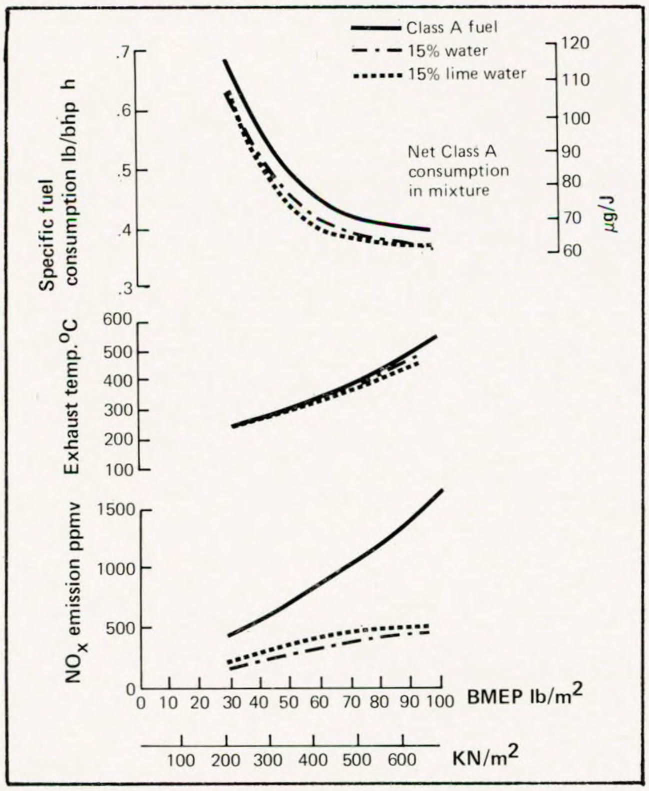


FIG 21 *Single cylinder Gardner diesel results on class A and water emulsions 1500 RPM*

3.4.2 *Engine Tests*

The engine was operated throughout the full load range at three constant speeds i.e. 1000, 1500 and 2000 rev/min. Standard diesel fuel was used throughout the

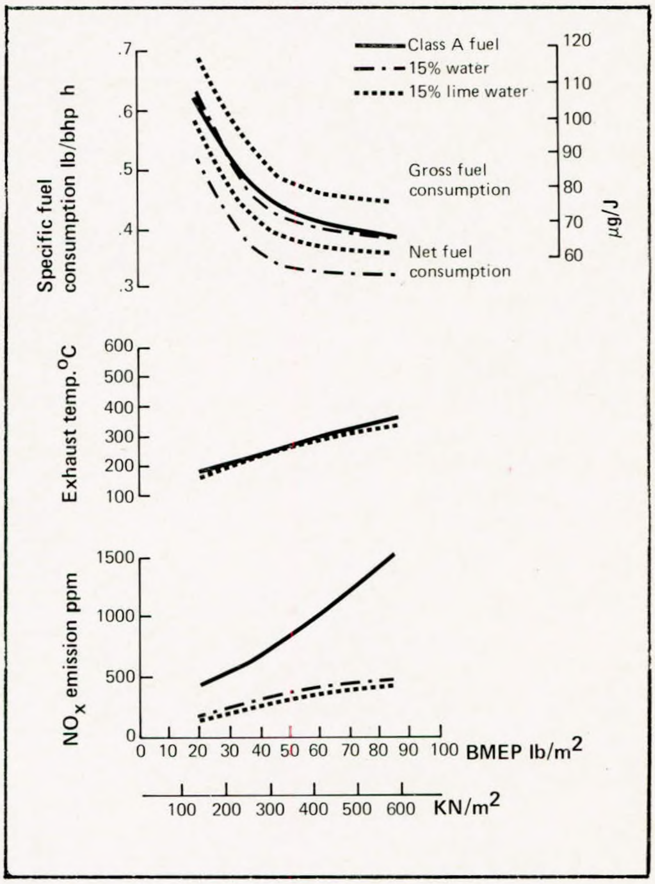


FIG 22 *Single cylinder Gardner diesel results on class A and water emulsions 750 RPM*

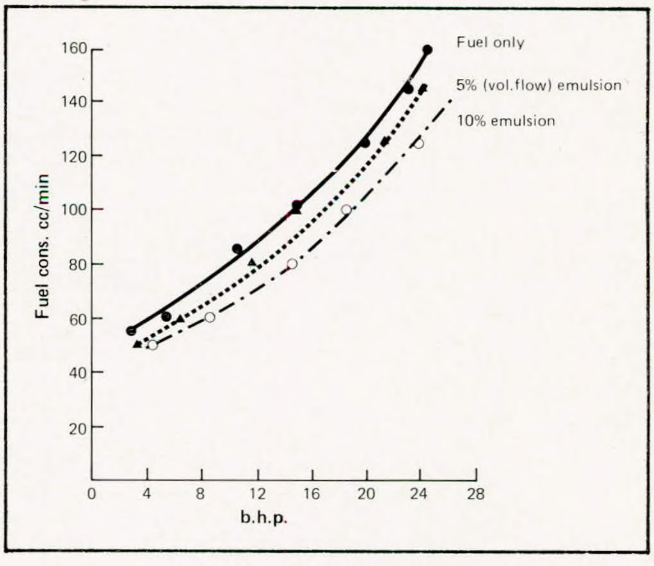


FIG 23 *1000 RPM tests*

tests – 5% and 10% water/fuel emulsions were tested. Test results are shown in Figs. 23 and 24.

3.4.3 *Results*

3.4.3.1 *1000 Rev/min*

The net fuel consumption was improved

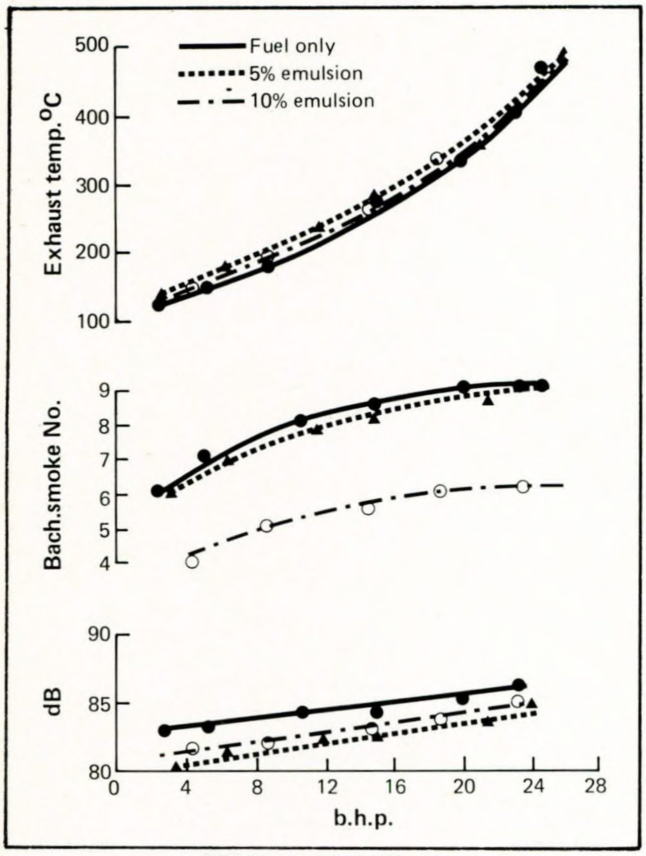


FIG 24 *1000 RPM tests*

throughout the load range by both the 5% and 10% emulsions. Figure 23 shows that the 5% emulsion gave a 6.9% saving and the 10% emulsion gave an apparent 17% saving at 18 bhp.

Exhaust temperatures running on 5% emulsion were 5% higher and on 10% emulsion 3% higher (See Figure 24).

Exhaust smoke was visibly improved throughout the load range, the Bacharach Smoke No. being reduced on 5% emulsion from 9 to 8.5, a 5.5% improvement. On 10% emulsion the improvement was dramatic, from Bacharach No. 9 to 6, a considerable improvement (See Figure 24).

Of particular interest to this engine was the variation of noise levels measured with change in water content as shown in Figure 25, suggesting in turn, that some significant changes must be taking place within the combustion chamber which are a question of debate. Apart from a change in intensity there was also a noticeable change in the frequency spectrum – more room for conjecture. All the above improvements were relatively constant throughout the load range performed at 1000 rev/min.

3.4.3.2 *1500 Rev/min*

The net fuel consumption was improved throughout the load range by a 5% emulsion, the improvement being less than the gains obtained in the 1000 rev/min tests, approximately 3% when delivering 27 bhp, as can be seen from Figure 25.

Exhaust temperatures running on 5% emulsion were 14% higher (see Figure 26).

Exhaust smoke was, again, visibly improved: the Bacharach No. being reduced from 8 to 6. (See Figure 26).

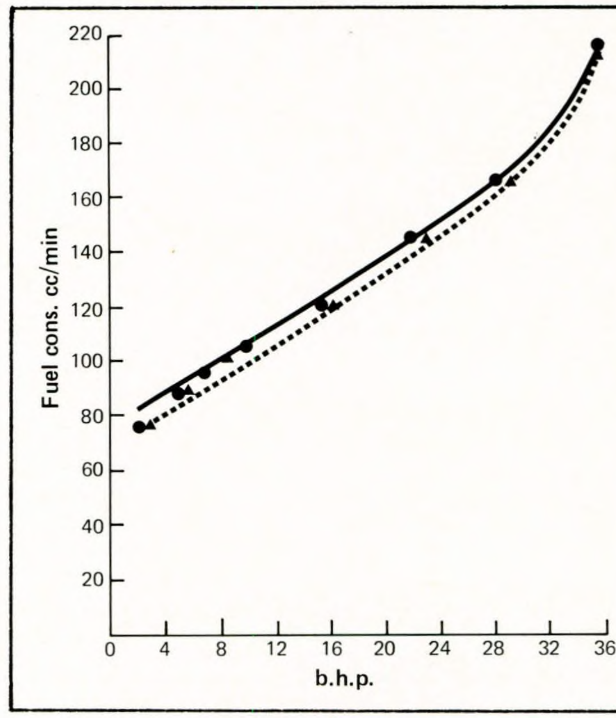


FIG 25 *1500 RPM tests*

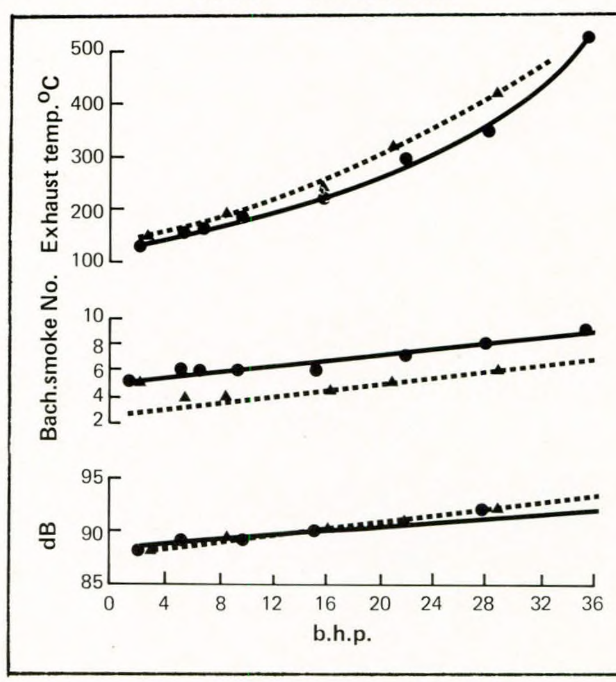


FIG 26 *1500 RPM tests*

The noise level was initially reduced but at approximately 14 bhp the curves crossed and the noise level running on emulsion increased. (See Figure 26).

3.4.3.3 *2000 Rev/min*

Running on 5% emulsion the improvement in net fuel consumption was 2.5% - 3% when delivering 34 bhp (See Figure 27).

Exhaust temperatures were also increased by 5% at the same bhp (See Figure 28).

There was no apparent difference in noise levels noticed between running on pure fuel and running on emulsion. (See Figure 28).

3.5 *Bedford Diesel Engine Trials*

This particular engine was selected as being a typical high speed 6 cylinder "workhorse" power plant used extensively in the automotive and allied fields. Being assembled in the laboratory of the Department of Marine Engineering at the University the test facility had the advantage of total accessibility and in consequence could be operated for considerable periods of time. The results presented, therefore, have been consolidated over a period of two years, are quite repeatable and to some extent have been consolidated by an "on the road" emulsified fuel experimental programme.

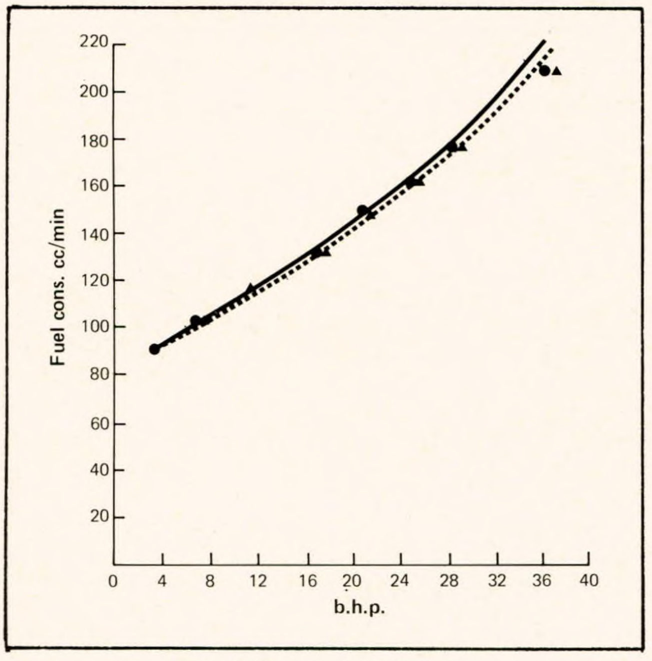


FIG 27 *2000 RPM tests*

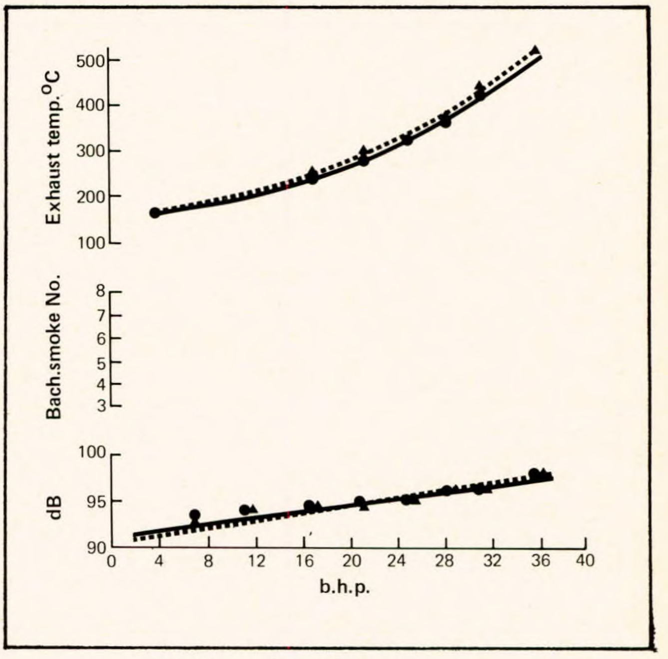


FIG 28 *2000 RPM tests*

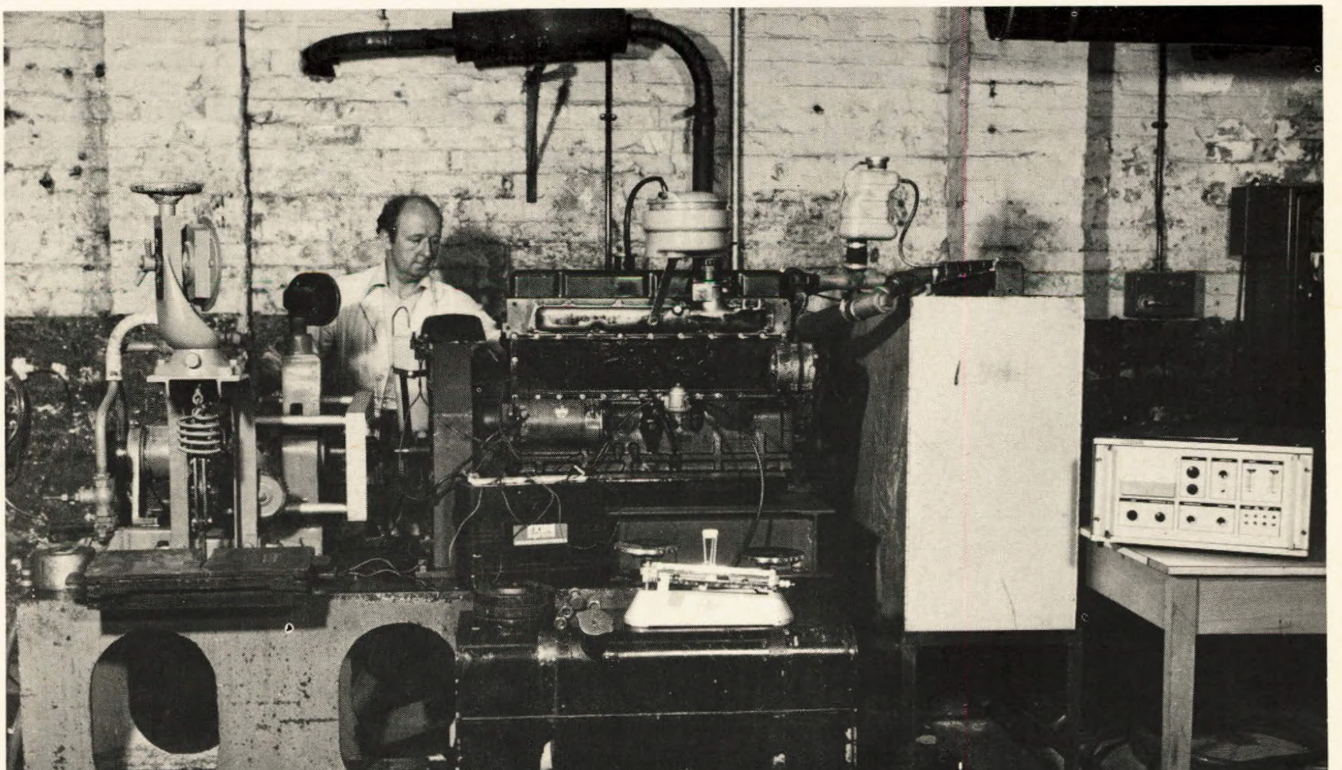


FIG 29 *High speed test bed*

3.5.1 *Experimental Facility*

The photograph Figure 29, shows the basic test assembly consisting principally of a six cylinder 330 $in.^3$ Bedford diesel engine, and a Heenan and Froude DPX3 water dynamometer. The bore and stroke of the engine are nominally 4.063 and 4.250 inches respectively, giving a capacity to produce approximately 85 bhp and 2450 rev/min.

The engine build was of normal production format with standard head and pistons consisting of an offset toroidal combustion chamber operating at a compression ratio of 17 to 1. The fuel system consisted of a C.A.V. DPA rotary fuel pump with complementary "four hole" fuel injectors operating at a nominal 175 atmospheres.

The engine was directly coupled to the dynamometer/tachometer assembly which was itself capable of absorbing 250 bhp at 6500 rev/min.

Originally, the fuel flow was read by carefully calibrated flowmeters which were later replaced by a weigh scale system to improve accuracy and repeatability. Water was supplied directly to the emulsifying device and in consequence had no effect on the accuracy of measurement of fuel flow. Figure 30 indicates system assembly.

3.5.2 *Experimental Procedure*

For the purposes of this test programme the engine parametric map was defined by six test points at speeds of 1400 and 2450 rev/min and load values of 20, 60 and 95 lb and 40, 60 and 93 at the lower and higher speeds respectively.

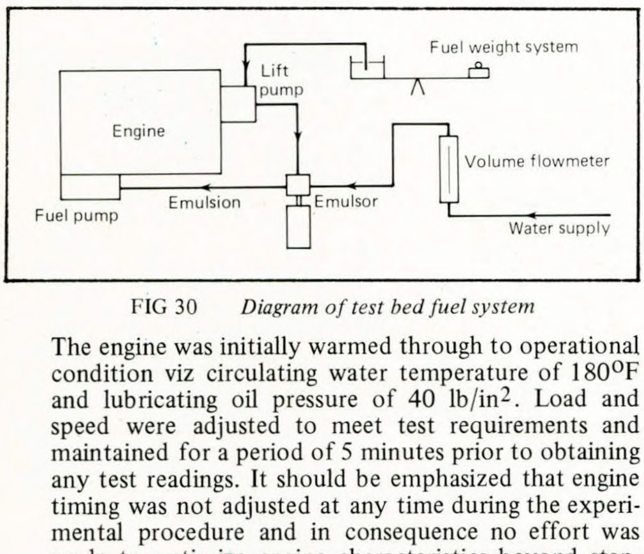


FIG 30 *Diagram of test bed fuel system*

The engine was initially warmed through to operational condition viz circulating water temperature of 180°F and lubricating oil pressure of 40 lb/in^2. Load and speed were adjusted to meet test requirements and maintained for a period of 5 minutes prior to obtaining any test readings. It should be emphasized that engine timing was not adjusted at any time during the experimental procedure and in consequence no effort was made to optimize engine characteristics beyond standard to improve performance when operating on emulsified fuel.

To ensure compatibility in fuel line pressure the emulsifying device was run throughout all tests – fuel and emulsion.

The normal test process consisted of stabilizing engine performance on pure fuel then admitting water via the emulsifier whilst maintaining load and speed. Concentration of water to fuel ratio was systematically increased and engine power maintained. Readings were taken at increments once the system had stabilized. Fuel rate was originally measured by flowmeter and subsequently by time/weight method.

Following the retrieval of all necessary data at one speed and load the latter was reset and the tests repeated.

Fuel flow values were in all cases obtained in mass/unit time, brake horsepower was calculated using the standard dynamometer constant.

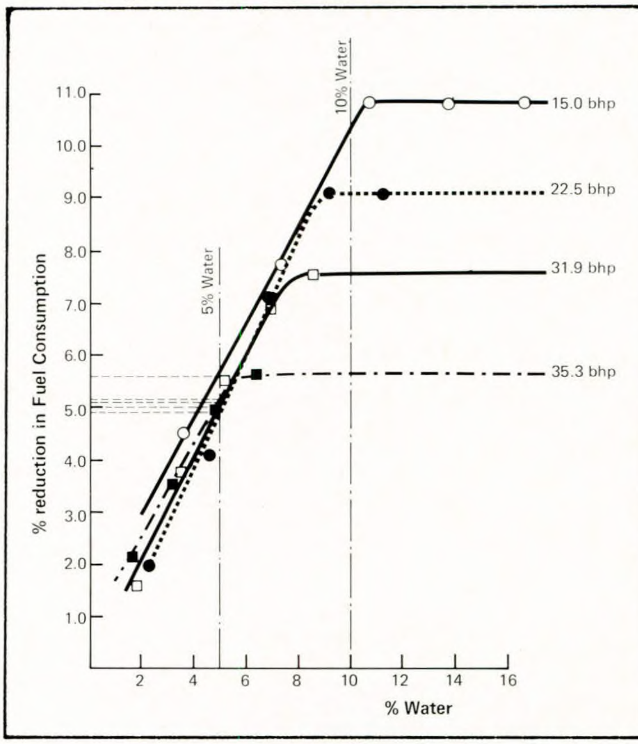


FIG 31 *% reduction in fuel consumption vs % water content @ 1050 rpm*

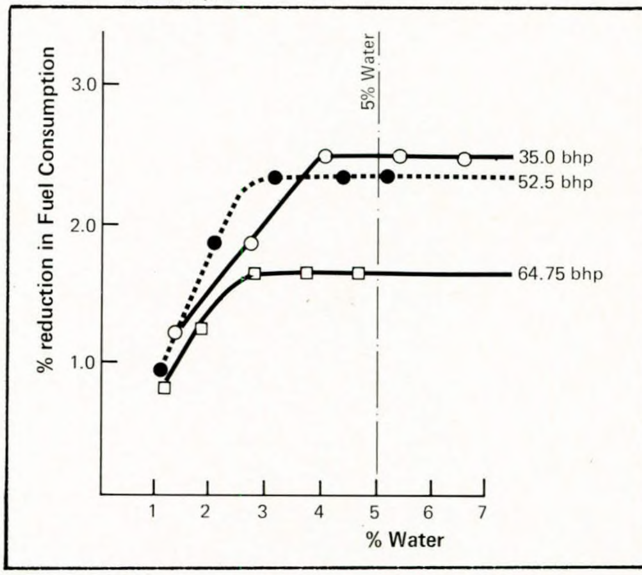


FIG 32 *% reduction in fuel consumption vs % water content @ 2450 rpm*

3.5.3 *Results*

Figures 31 and 32 have been selected to demonstrate quite emphatically the effect of water in oil emulsions on this type of engine. Of particular interest is the "knee" effect i.e. the percentage fuel saved being proportional to the water introduced up to a clearly definable point, thereupon a reversal is experienced. The magnitude of this optimum position decreases with increase in engine load being, typically, 1½ to

2% at full load and 10-12% at low load. This overall tendency has been noted on other engines and is becoming an accepted phenomenon which may be used most beneficially. For example, the flow rate of water may be kept constant irrespective of engine power condition in order to provide optimum fuel economy i.e. at 1½% to 2% of maximum fuel oil flow, minimizing complexity of installation.

Arguably, engines are designed to provide optimum performance characteristics at the higher power condition both in terms of atomization and combustion profiles and in consequence any significant savings that may be made will be obtained at the least efficient position.

Figures 33 and 34 show BSFC as a function of bhp and summarize the effect of burning a range of concentrations of emulsified fuels. At 1400 rev/min the improvements range from 7.8% at low load to 2.8% at the high load condition. Curves applicable to the 2450 rev/min situation display similar trends with the bandwidth of improvement lying between 4.4 to 2.7%.

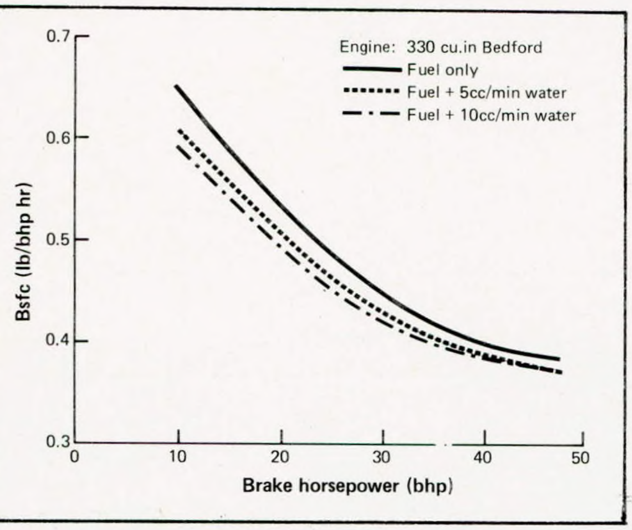


FIG 33 *Effect of emulsified fuel on brake specific fuel cons. at 1400 RPM*

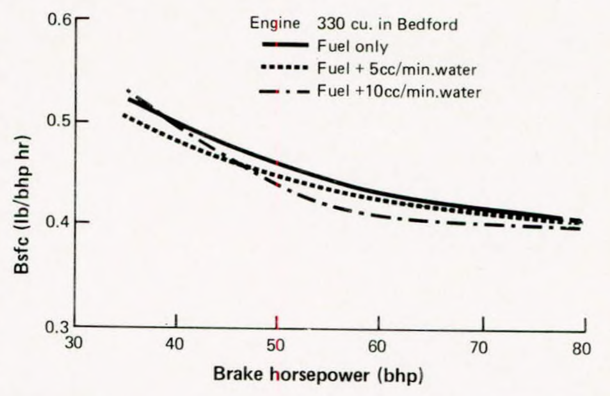
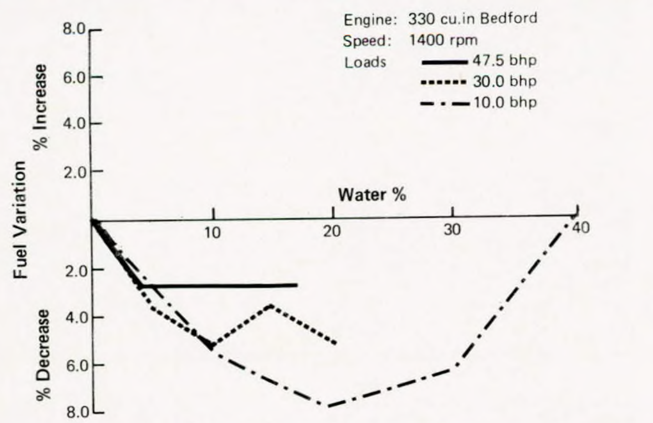


FIG 34 *Effect of emulsified fuel on brake specific fuel cons. at 2450 RPM*



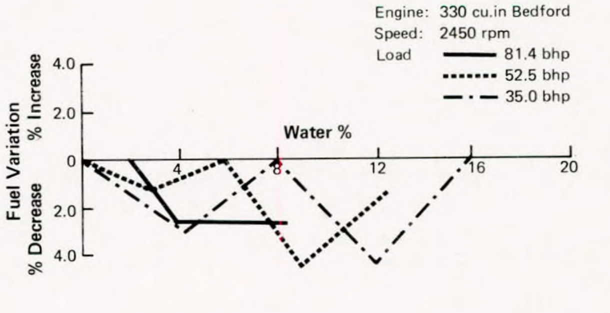


FIG 35 (a) *Fuel variation with water addition* and FIG 35 (b) *Fuel variation with water addition*

A phenomenon not previously recognised is shown in Figures 35a and 35b. At the load operating condition circa 35 bhp, fuel consumption apparently peaks at 4% water content and again at 12% exhibiting a distinct increase in consumption between these two points and again after, i.e. at 16%. This is by no means a high water concentration at this operating point and offers an inexplicable anomoly. All results are plotted on a continuous basis during the test programme and, therefore, any erroneous results would be quickly identified. Each fuel recording was repeated on several occasions, both when operating on emulsions and base fuel, with unusual or unexpected results being given specific attention. The results, therefore, would appear to be largely correct to the extent that their specific peculiarity cannot be appended to the "cry" of experimental error. Research has indicated that when results of this type are recorded it is usually in the low load high speed situation; leading to the premise that optimization of the water content in the fuel to obtain a reduction in fuel consumption at high speeds is less critical at the higher than at the lower loads.

A cursory glance at the above results indicates that, depending upon the operational requirements placed upon an engine of this type, fuel economies can be obtained by the use of emulsified fuels ranging from 2 to 8%. Although scientifically invalid, road tests with a similar engine subjected to alternately simulated motorway and rural traffic conditions showed similar performance improvements leading subsequently to a system being fitted to a bus engine operating a usual town service.*

* Passenger Transport Executive – Newcastle Upon Tyne

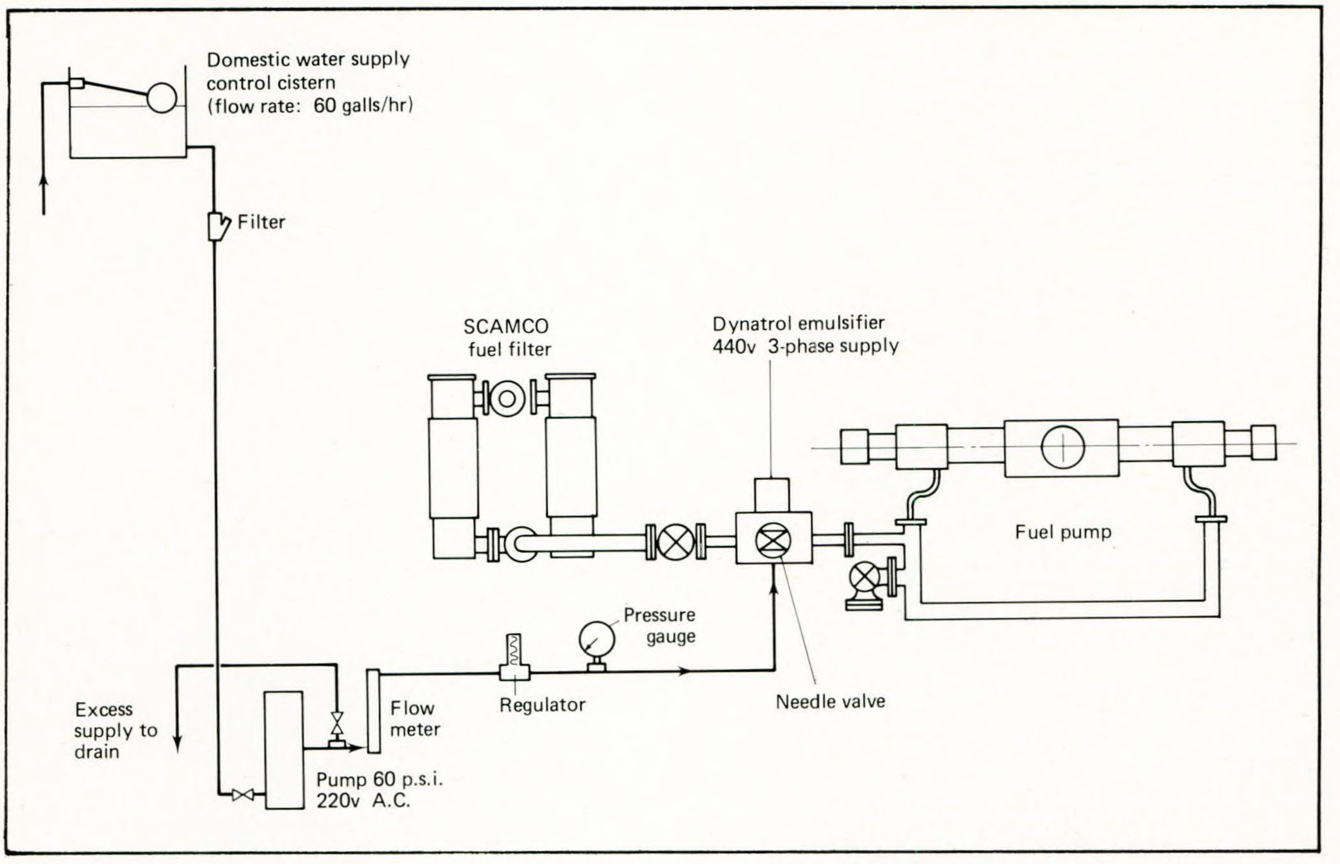


FIG 36 *Test bed arrangement for burning water/fuel emulsion*

3.6 *Slow Speed Diesel*

An opportunity was gained this year to burn a mechanically produced emulsion in a Doxford "J" engine – i.e. a 6 cylinder opposed piston two stroke slow speed engine which was fully instrumented and undergoing acceptance trials. Nominal bhp was 12000 at 124 rev/min.

Figure 36 shows the assembly diagram for the tests and Figure 37 the engine on test, with emulsifier fitted. The actual period available for trial was limited to a maximum of two days and as the first was used to calibrate instrumentation the results were actually obtained over a period of one day only.

Although the majority of tests were undertaken at 90% load with water content ranging from zero to 5.6% by weight, a series of tests were completed at 75% power with a water inclusion of 3.6%.

Difficulties were encountered with the fuel and engine timing as the system attempted to absorb the additional fluid flow – no modifications being permitted as the engine was to be shipped as a standard production unit – consequently the results regarding fuel consumption must be considered suspect. However, the tendency shown by the results appeared to follow previous trends – a small but perceptible reduction in specific fuel consumption at the intermediate power. If time had permitted it would have proved of considerable interest to attempt to optimize water content in the fuel oil to the apparent fuel saving involved. Whereupon engine injection/timing difficulties would have been obviated. In any event there was no loss in power or change in fuel consumption recorded at the 90% MCR condition when operating on emulsion, which is in itself a significant recording.

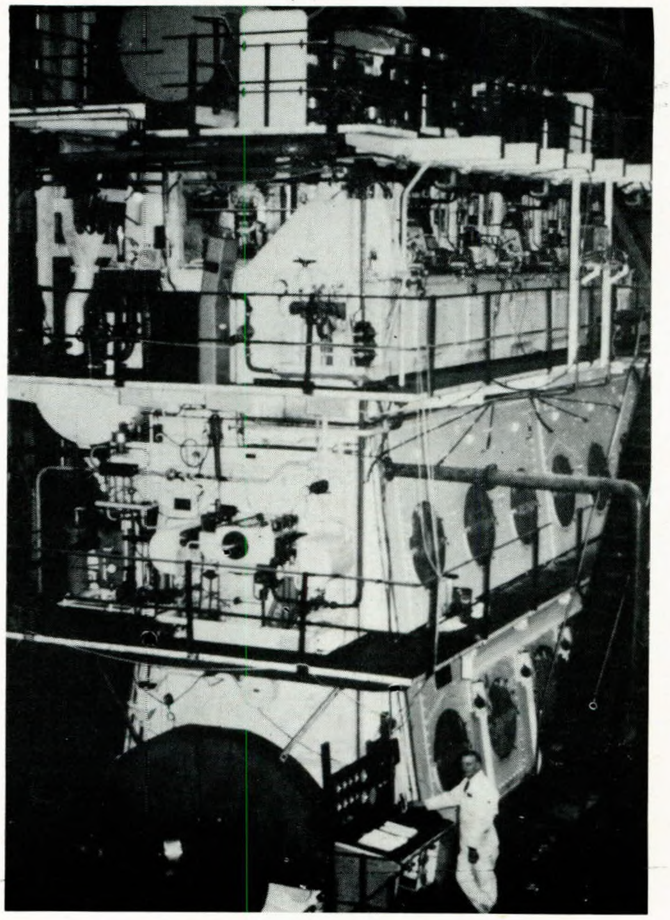


FIG 37 *Doxford J engine*

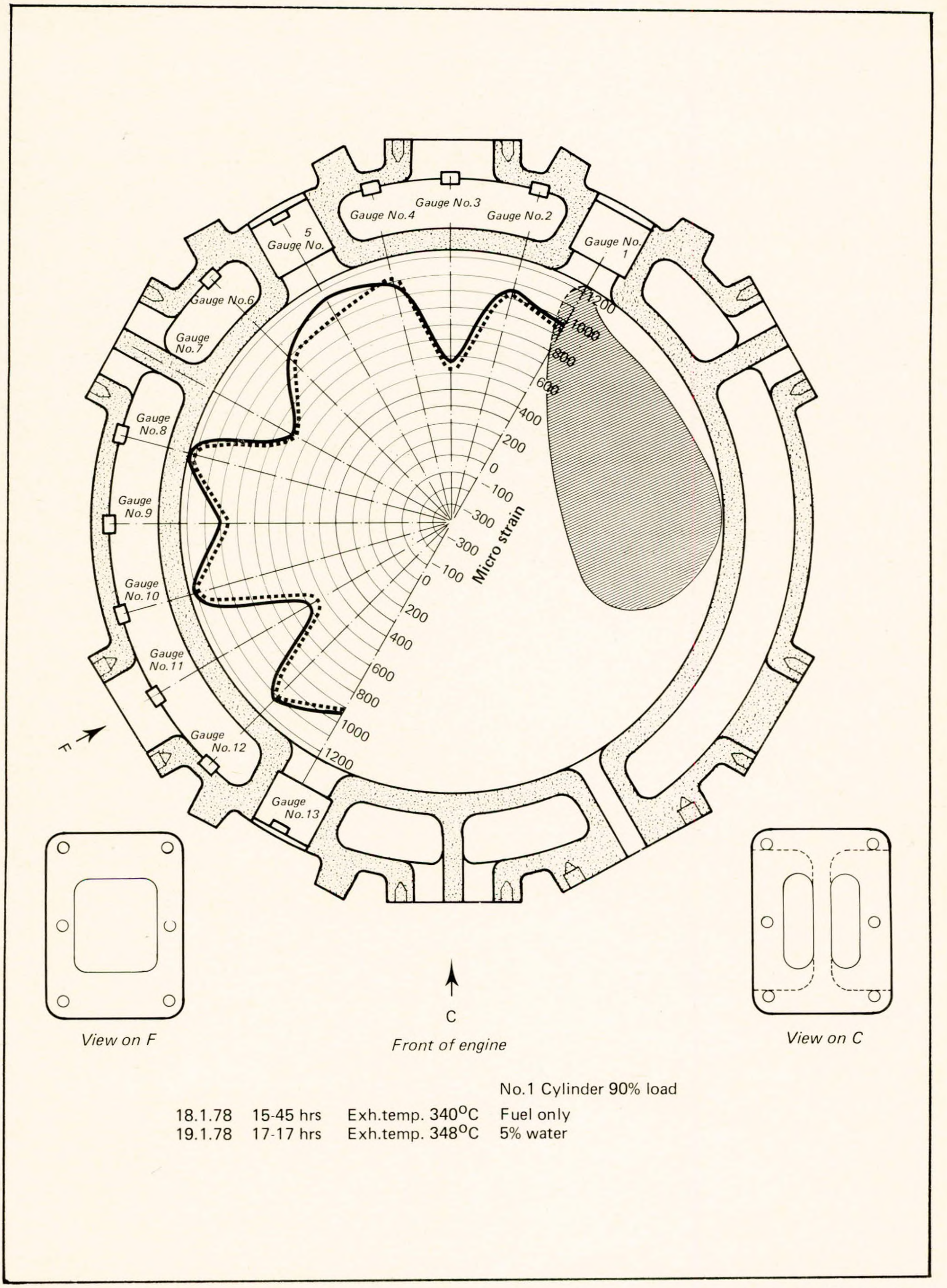


FIG 38 *Combustion belt temperature strain comparison of strain distribution for engine running at 90% load on straight fuel oil and emulsified fuel*

Of further interest, cylinders No. 1 and 2 were fitted with strain gauge arrays of 13 to each cylinder. A Baldwin strain indicator was used throughout the tests which had the capacity to indicate the steady state strain which occurred during scavenge giving, in turn, an indication of temperature strain superimposed on the cylinder during combustion.

Records were taken with the engine running on straight fuel (bunker "C") and compared with those obtained during the combustion of emulsion. A 2.2% inclusion of water in the fuel resulted in a nominal reduction in temperature strain of approximately 3%. (Fig. 38) shows typical results.

Although scientifically inaccurate the tendency shown by these trials is most encouraging and further more exhaustive test procedures are hoped for in the future.

3.7 *Other Tests*

The author has been directly involved in several other test programmes including an intensive programme instigated by the U.S. Coast Guard at the South West Research Insitute, San Antonio, Texas. The engine involved was a single cylinder L.E.C. displacing a nominal 42.8 in.^{3} open chamber design using a 'Mexican Hat' piston configuration – nominal compression ratio 16.7 to 1, and was accurately instrumented with regard to combustion performance, exhaust emission and power generated. Further details of

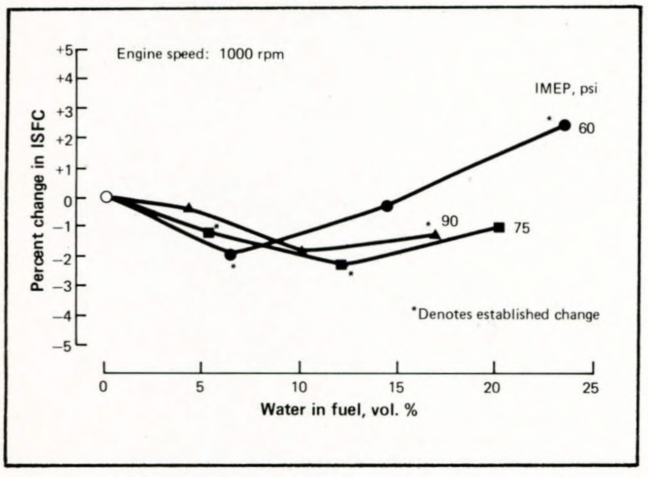


FIG 39 *Effect of emulsified fuel water content on engine specific fuel consumption at 1000 RPM*

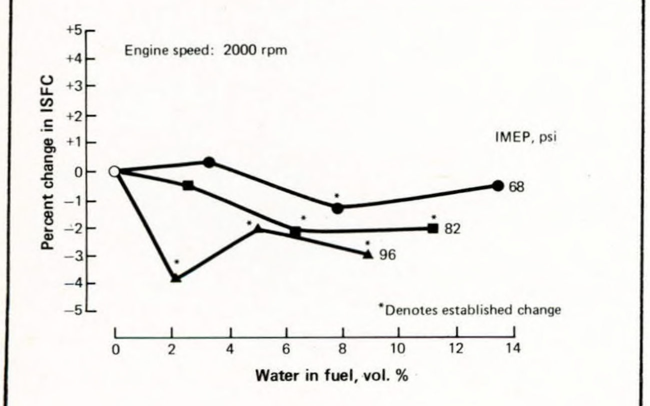


FIG 40 *Effect of emulsified fuel water content on engine specific fuel consumption at 2000 RPM – dynatrol emulsifier*

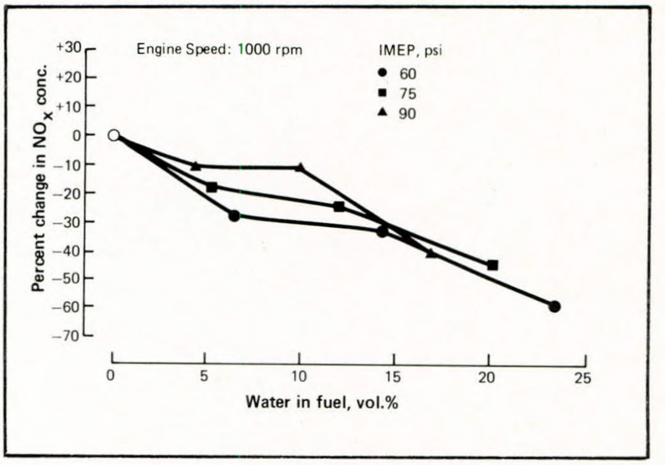


FIG 41 *Effect of emulsified fuel water content on oxides of nitrogen concentration at 1000 RPM*

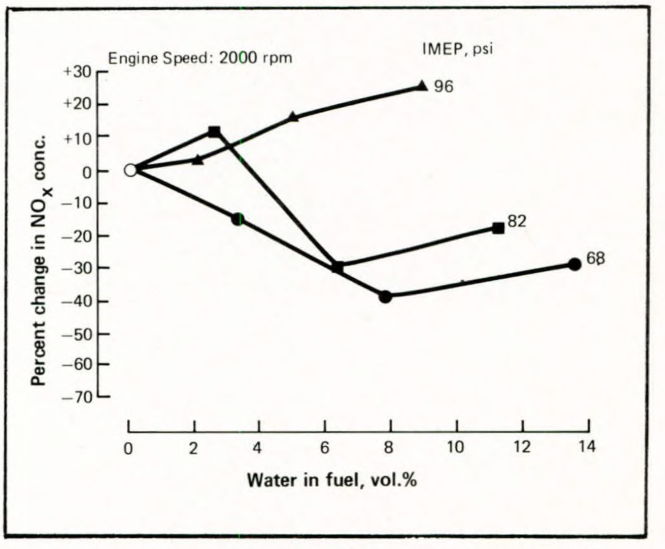


FIG 42 *Effect of emulsified fuel water content on oxides of nitrogen concentration at 2000 RPM*

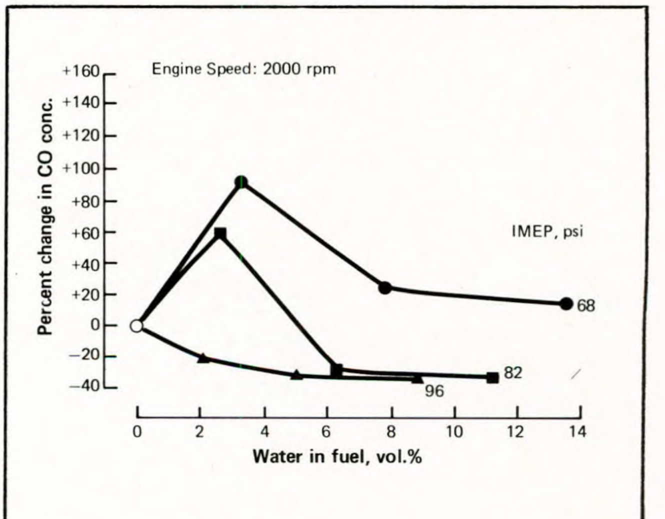


FIG 43 *Effect of emulsified fuel water content on carbon monoxide concentration at 2000 RPM*

the assembly and tests are available in [20], recently released. Of passing interest, the engine, which had a maximum speed capability of 2500 rev/min could be regulated to within plus or minus one rev/min.

Figures 39 and 40 are reproduced from this report and show statistically averaged data measured over a six week period. The tendency is as indicated before. Figures 41 and 42 show the effect of water concentration on the production of oxides of nitrogen endorsing the conclusion that relatively high water concentration is demanded to show a significant decrease in NO_x emission.

Figure 43 is typical of the effect of emulsions in CO concentration in the exhaust stream.

Other programmes include effort on a multi-cylinder high speed engine in the Eastern USA which exhibited 5-7% fuel economy coincident with meeting the Californian specification on emission control. It is interesting to note that there is a clearly definable limit which may be exercised on diesel engine emission control using conventional techniques of timing etc., i.e. 5gm/hp/h. Beyond this point an alternative system is demanded – emulsified fuel combustion techniques have demonstrated a capacity to reach 2 gm/hp/h without any reduction in engine performance.

Further programmes of effort are continuing with various industrial and consultant organizations, but these are currently considered to be commercial in confidence at the time of writing.

4. FUTURE PROGRAMME

The Department of Marine Engineering at the University of Newcastle upon Tyne has been funded by the Department of Industry to undertake a series of exhaustive tests to determine, on a scientific basis, the effect of burning emulsions in a range of diesel engines.

Currently, emulsified fuels are being burnt in the Department's own extensively instrumented Ruston 6 APC using two homogenization and one emulsification system. (Figure 44). A broad range of fuels are being tested and the quality and structure of the emulsions assessed by photo-spectrographic techniques.

In parallel with this initial medium speed optimization programme fuel system endurance trials have been investigated. Emulsions of known water content have been circulated over periods of 500 hours through a fuel system test assembly with all components being subjected to rigorous inspection and measurement before commencement and at termination of tests. The objective being to determine if any unusual corrosion, erosion or wear tendencies will occur due to the prolonged passage of emulsified fuel.

Assuming that these arduous optimization trials show an encouraging result in terms of fuel consumption, exhaust valve operation, general reliability – start and operation, etc. – further endurance trials will be investigated followed by extensive operation at sea.

A third and equally exciting parallel phase of the programme is the evaluation of the response of a slow speed diesel engine to the combustion of emulsified fuel continuing from the termination point of the trials previously mentioned, with positive results leading to monitored operation at sea.

A gas turbine test programme has also been negotiated with a prominent manufacturer and the Royal Navy and is due to commence preliminary trials shortly.

Naturally several UK manufacturers are involved in the pursuit of these programmes and it is to be hoped that this country may establish not only a lead in this field but also a commercial advantage based upon the experience and data which will become available in the near future.

5. THEORETICAL ASPECTS

Comments on the theoretical evaluation of the combustion of emulsified fuels have been left to the end of the paper because no mathematical treatise is yet available

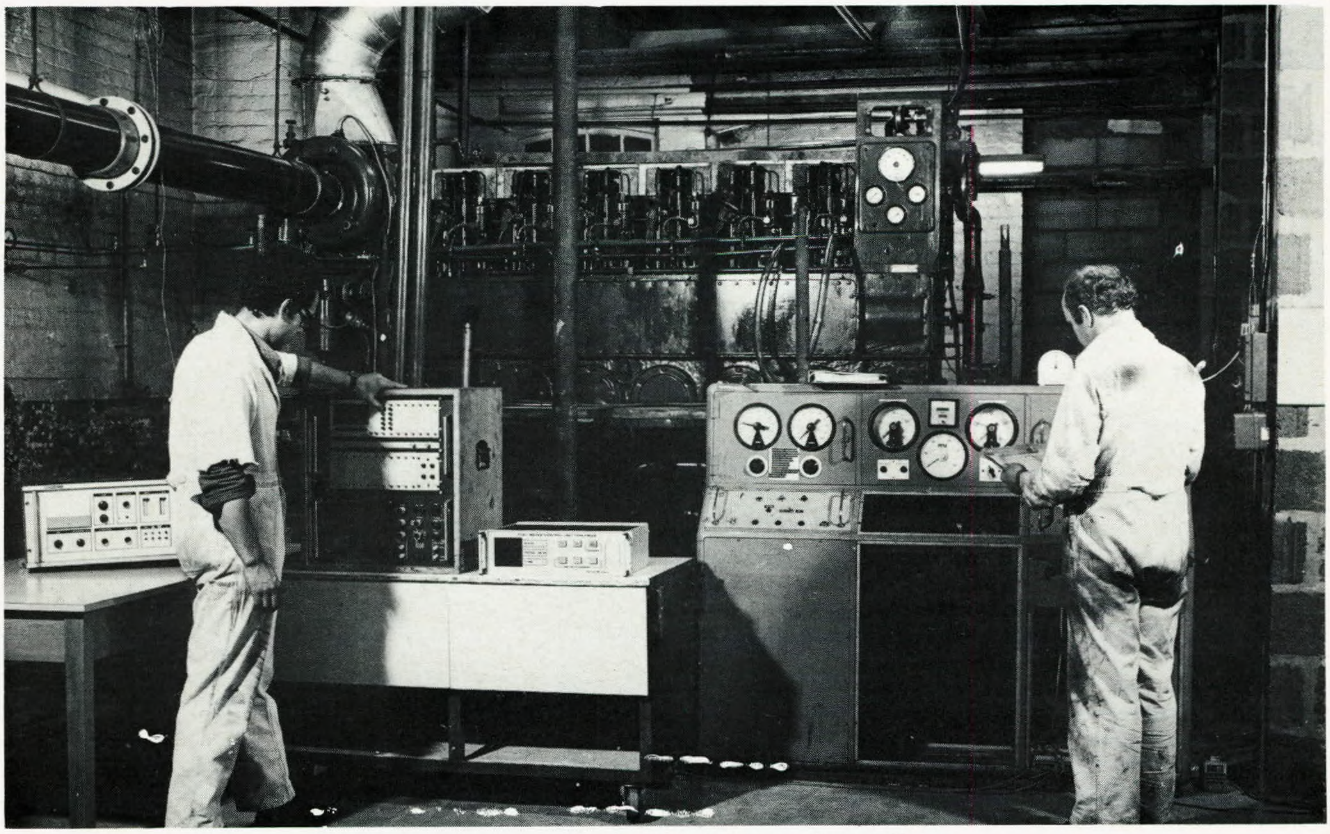


FIG 44 *Test bed at University of Newcastle upon Tyne*

which will adequately describe the process involved. Consequently, observation of the experimental results obtained seems to be a more beneficial exercise.

In low pressure combustion process (boilers) it is relatively safe to postulate that water in oil emulsions exhibit some advantages due to the oil, when ignited, super heating the water causing a rapid rise in incipient pressure. This, in turn, causes a rapid expansion or explosion which shatters the integrity of the enveloping oil film resulting in the micro explosion phenomenon often displayed in controlled experiments. A process of secondary atomization occurs promoting an improvement in combustion efficiency.

In diesel engine combustion chambers, however, the most likely effect of including water in the fuel at high power is the suppression of dissociation, due to the quenching effect involved thereby limiting maximum temperature. At intermediate and low powers where the atomization/ combustion process is not so efficient the micro explosion theory probably operates in conjunction with a tendency to reduce dissociation and the results are more marked.

The quenching phenomenon may be supported by the general tendency of emulsified fuel to reduce NO_x which is itself temperature dependent. Interestingly, large amounts of water are required to limit the formation of NO_x which tends to support the hypothesis.

However, at high loads and speeds, an excess of water over that required to marginally improve fuel consumption paradoxically results in an increase in NO_x output.

It could be postulated that for each percent of water added over the optimum for fuel economy, a further quantity of oil is required to maintain power, the chamber becomes overcharged and in consequence efficiency falls and temperatures rise.

Reference to available data (Figs. 40 and 43) indicates that fuel savings are evident beyond the optimum water content appropriate to the full power situation even though production of Oxides of Nitrogen increase. Some ignition delay could be involved followed by a rapid rate of heat release leading to temperatures compatible with production of additional NO_x.

Furthermore, ignition could be delayed to such a degree that combustion is incomplete or continues in the exhaust. These fundamental anomalies and many others need to be resolved in order that optimal use of the phenomenon may be realised. Hopefully, the programme outlined here will provide at least a guide to further understanding and utilization.

6. FINAL COMMENTS

Experiences over the past few years have indicated that the application of correctly produced water in oil emulsions to combustion plant will result in perceptable changes in performance under certain operational conditions namely:

- Reduction in NO_x
- Improvement in specific fuel consumption
- Reduction in exhaust gas temperature
- Reduction in thermal stress
- Variation in flame configuration
- Cleaner combustion

However, disadvantages include environmental protection of water involved, marginal increase in complexity, fuel system changes and "user" resistance!

Hopefully benefits will outweigh disadvantages and the application of the phenomenon and technology involved will provide, at least, an interim arrest to problems of vanishing liquid hydro carbon supplies.

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Discussion

DR F ORBECK FIMarE (Doxford Engines Ltd) felt that Professor Thompson had dealt in a most professional manner with a subject of considerable interest to both operators and designers of heat engines. The oil crisis and the increased urgency to use fuel oil more economically had produced a number of poorly substantiated claims on reductions of fuel consumption obtainable by using water in the fuel oil. Professor Thompson's paper would help to put the subject on a firmer scientific basis and be of great help to those who wished to draw advantage from that technique. However, Dr Orbeck wished the author to clarify several points.

Reference was made to thermal NO_x and fuel related NO_x. Dr Orbeck thought the major part of the NO_x in the exhaust was created during combustion and that it was directly related to the maximum temperature.

In Fig. 4, the ratio of water to gas oil was stated as 0.8 which surely, must be the ratio of gas oil to water?

The paper dealt comprehensively with the use of water-in-oil emulsions in boilers and gas turbines, as well as in high and slow speed diesel engines. The slow speed diesel tests were carried out at Doxford and, although some beneficial trends were established, the improvements were smaller than in the other applications. One reason might be that the engine was already well-tuned for fuel consumption. As shown in Fig. 16, the improvement obtained in boilers was reduced as the boiler efficiency increased and reached zero at 84% efficiency. However, it seemed that interesting information could be obtained from the effect on the flame in boilers which was given in Figs. 10 to 15. Addition of water increased the length of the flame considerably.

In a recent paper, Henshall and Orbeck* gave fuel injection spray patterns for a Doxford 58JS3 engine and pointed out the importance of finding a spray pattern which reached the main part of the air quickly (Fig 23). It seemed from the flame patterns that water in the oil might change the spray patterns considerably and that a new matching of injectors would be required for optimum performance. Professor Thompson's comments would be appreciated.

Certainly the results presented in the paper were convincing and further tests on the Doxford engines would be welcome as soon as they could be fitted into the company's programme.

MR S R NORRIS-JONES (Ricardo Consulting Engineers Ltd) found the paper highly informative and said that his contribution would be to give some results obtained at Shoreham from two different engines.

Figs. 45 and 46 showed results obtained from a 216 mm bore single cylinder engine running at 1000 rev/min and operating at rated output of 21 kg/cm^2 bmep. The engine was run with two different injection builds, one giving good smoke and performance with a maximum line pressure of 1200 kg/cm^2, and the other very poor performance with maximum line pressures of c. 850 kg/cm^2. In each case the cylinder pressure was set to the same limit of 144-147 bar at 21 kg/cm^2.

Fig. 45 showed that, for the "good" performance build, the emulsified fuel had no effect on fuel consumption and a marginal effect on smoke, whereas the performance of the "poor" injection build was dramatically affected: over a 6% reduction in fuel consumption and a large reduction in smoke levels. On the emission side NO_x levels were reduced by 16 to 20% with both "good" and "poor" injection systems when 25% by volume of water was added.

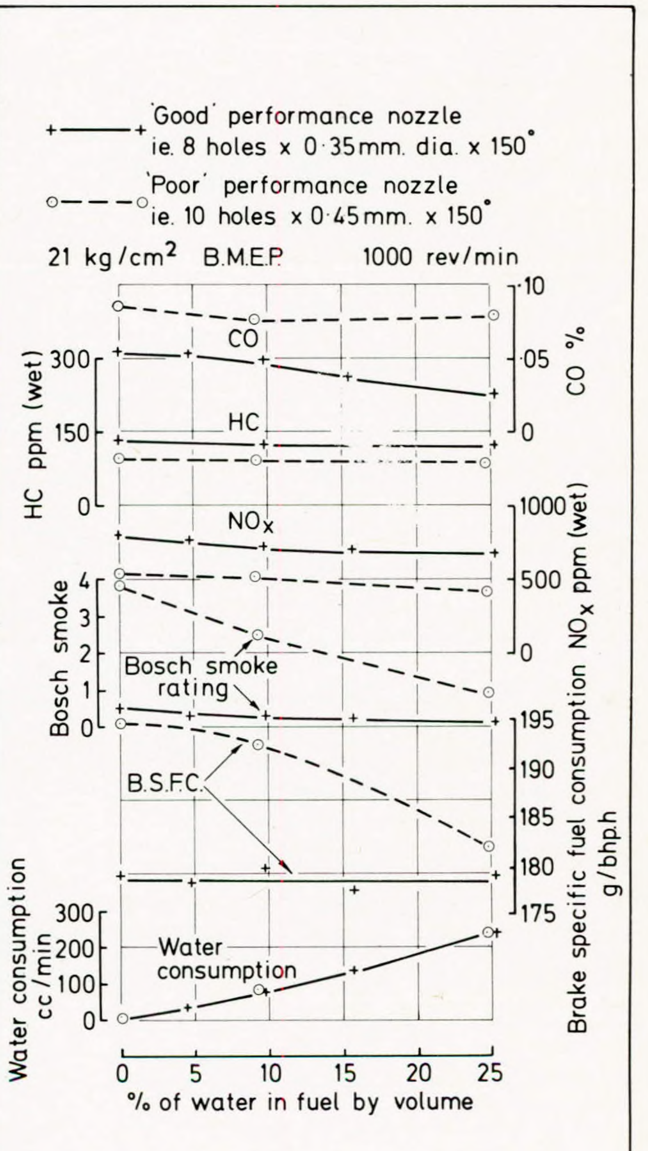

FIG 45 *Results from first engine*

Fig. 46 showed a similar set of curves for the light load condition of 6.6 kg/cm^2 bmep. At that condition, once again, the "poor" injection build performance was dramatically affected, but also some benefit was seen for up to 10% water on the "good" system.

It was interesting to note from these results that, with a well matched combustion/injection system and relatively high fuel line pressure limits, the benefits to be obtained from water emulsion were in NO_x reductions, rather than in fuel consumption or smoke. For engines with poor combustion resulting from low fuel line pressure limits, the choice for improvements in fuel consumption and smoke seemed to be between higher pressure injection systems and emulsified fuel.

*HENSHALL S H and ORBECK F 1978. "The Doxford Three-Cylinder Engine" Trans NECIES Vol 95, Trans IMarE Vol 91, Part 1.

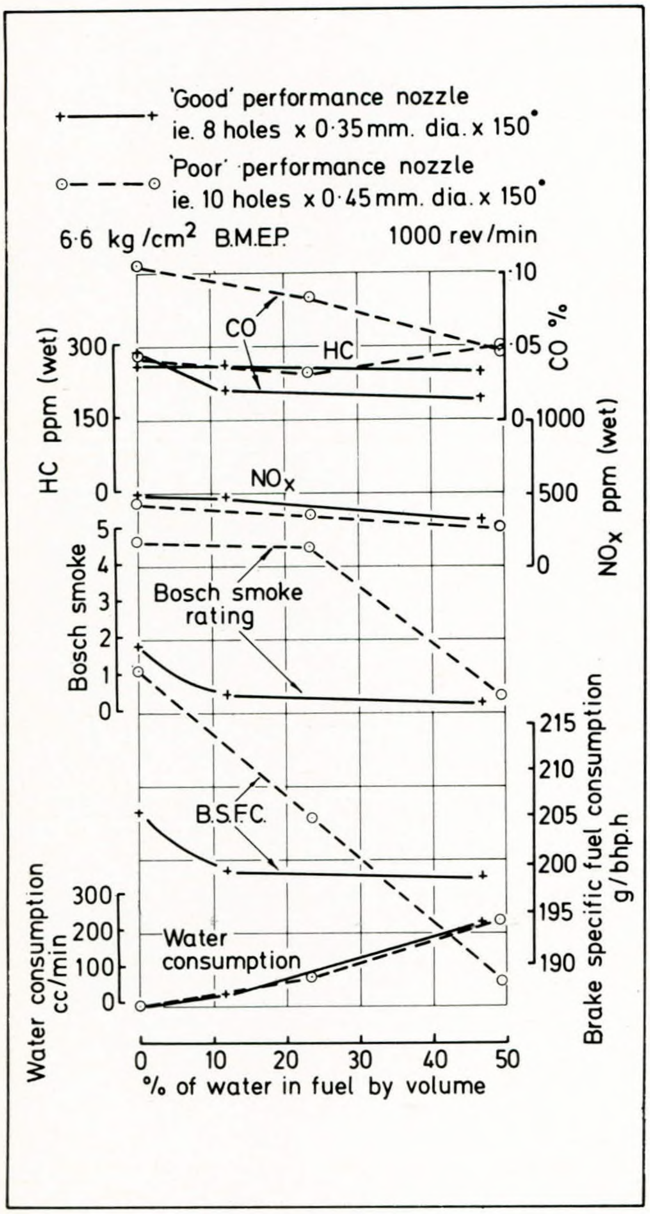

FIG 46 *Results from second engine*

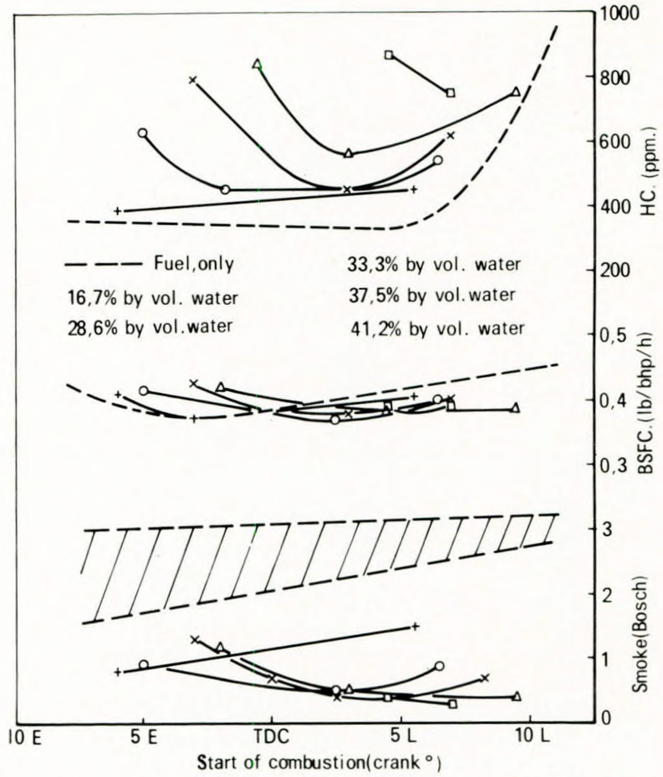

FIG 47 *Showing that HC levels were always higher than the 'base-line'*

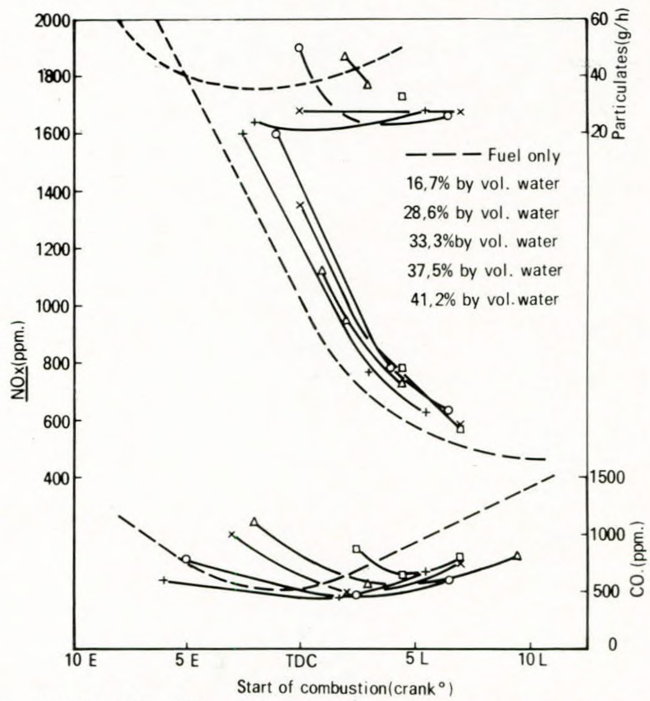

FIG 48 *NO_x, CO and particulates against start of combustion*

Turning to the smaller engines, Ricardo's work to date had been carried out on a four cylinder, direct injection, automotive type engine of similar swept volume per cylinder to the Bedford engine used by the author. It could be seen from Fig. 47 that the effect of various quantities of water on smoke level, fuel consumption, and unburnt hydrocarbon levels at various timings for start of combustion, showed that HC levels were always higher than the "baseline". However, fuel consumption could be held at, but not made better than, the optimum "fuel only" levels at retarded timings. Smoke, as seen from other results, was dramatically reduced over a wide range of conditions.

Fig 48 was for similar conditions but showed NO_x, CO and particulates against start of combustion. Whilst CO and particulates were reduced at retarded timings, it was interesting to note that NO_x for a given start of combustion was slightly higher with water than without. Ricardo's explanation was that, although the water gave better mixing, the rates of cylinder pressure rise with emulsion were higher as a result of longer delay periods, and this increased the NO_x level. Figs 47 and 48 showed full load/full speed results for the engine, but a similar trend was observed over the complete load/speed range.

The conclusions from that work were that emulsified fuel enabled one to run at retarded timings to achieve low NO_x without suffering the penalties of high smoke and increased fuel consumption; however, the rise in HC emissions was very significant where combined HC/NO_x legislation was applied.

The work described was carried out on an engine fitted with a DPA fuel pump similar to that used on the

Bedford 330 engine tested by the author. Experience showed that the testing and analysis of the results became a very complex matter, because the DPA pump had an inherent characteristic of variable start/fixed end of injection which meant that at a given power setting, if water was added, the injection timing advanced; and any change noted might be the result of either the water or the timing change. Also, because of that characteristic, engines fitted with DPA pumps were tending to run at optimum timing for performance at full load conditions and then progressively more retarded from optimum as load was reduced. Mr Norris-Jones felt that if the results plotted in Figs 31 and 32 of the paper were to take account of the advance in dynamic timing which would have undoubtedly occurred the author would have seen a *pro rata* improvement in fuel consumption with injection timing and not water concentration. That was certainly clearly demonstrated by Ricardo's tests.

Finally, Mr Norris-Jones commented on a simple point which was often overlooked by those who advocated the use of emulsified fuels in vehicles. If water was added without any adjustment being made to the maximum fuel stop of the pump then, at full rack conditions, the engine would be receiving less fuel than normal, power would be reduced and fuel consumption improved as a result of the engine operating on a lower fuel consumption part of the load range curve. The same fuel consumption saving could be achieved by a straight engine derate. If, however, the fuel stop was adjusted then the first time the vehicle was run on straight fuel, the exhaust would be completely unacceptable.

Whilst he clearly remained to be convinced of the benefits of operating the diesel engine on emulsion, Mr Norris-Jones thought that the large smoke reduction achieved with emulsion demonstrated quite clearly that there was still great scope for improving the mixing process in the diesel.

MR W LOWE, C Eng FIMarE (Mirrlees Blackstone (Stockport) Ltd) congratulated the author on an extremely competent presentation of a very interesting paper. When his company first discussed a proposal for the work subsequently started at Newcastle, there were two practical questions which seemed to need answers before an emulsified fuel system had any chance of success in an engine or a boiler.

The first difficulty was to ensure a stable emulsion to avoid the later separation of the fuel and water. The work described in the paper seemed to avoid that problem by using an on-line emulsifier with no storage capacity between the emulsifier and the engine. The author was asked to comment on the stability of emulsion or to amplify the description of the system.

The second point was partially linked with the first and concerned the use of an emulsion in a fuel-injected system. What was the effect of the high fluid pressure and high shear rate of a jerk-pump system on the emulsion and, perhaps more importantly, what was the effect of the emulsion on the fuel injection equipment? Mr Lowe noted that the paper referred to 500 hour periods in a test rig to determine if there were any tendencies for corrosion, erosion or wear, but no results of these rig tests were described.

As an observation, he would point out that the two advantages which the use of an emulsified fuel in an engine might have, *viz.* the reduction of fuel consumption and the reduction of NO_x emissions, needed to be considered separately. The optimization of engine conditions to improve one of these would be different from that intended to improve the other. For example, without emulsified fuel, the level of NO_x emissions from an engine could generally be reduced by retarding the fuel injection timing. That would usually give an increase in fuel consumption and a reduction in maximum cylinder pressure. The turbocharger could then be rematched to increase boost and restore the maximum cylinder pressure and it was probable that the lower level of NO_x would be substantially maintained. Whether the fuel consumption went up or down for this turbocharger change would depend on the particular engine design. A comparison of, for example, specific fuel consumptions with and without the use of an emulsion should, therefore, try to compare like with like as closely as possible; the usual limitation which should be kept constant being the maximum cylinder pressure.

Author's Reply

Professor Thompson took the comments and queries in their order of submission and first of all answered the queries raised by Dr Orbeck.

With respect to stability, analysis had indicated that the stability of a mechanically produced emulsion (as opposed to one using surfactants) was a direct function of viscosity of the fuel oil. High distillates showed perceptible precipitation of water within 20 to 30 seconds, although heavy oils had stability levels varying from a few hours to several weeks, presumably due to the inclusion of natural surfactant material.

The author was in complete agreement with Dr Orbeck's comments relating to NO_x. However, Turner and Siezmund undertook research which was specifically concerned with the problem of NO_x production during the combustion process and, in consequence, found it necessary to isolate fuel-related NO_x.

The comment concerning ratio of water to gas oil alluded to in Fig 4 as 0.8 indicated in normal parlance, a 40% water content.

The author was quite prepared to accept that if a combustion process was manufactured to ideal conditions, producing a maximum permissible combustion efficiency, the inclusion of water in the fuel oil as an emulsion would provide little return in terms of improving combustion efficiency. However, those conditions were very rarely met outside the laboratory, if then, and consequently, the application of emulsified fuel concepts to the average product usually resulted in perceptible, and in most cases, significant improvements. A subjective view on the process involved suggested that emulsified fuel improved secondary atomization; it would appear unlikely that significant changes would have to be made to injector systems, particularly as at rated power the volume of water required to achieve maximum combustion efficiency was very small indeed and of similar magnitude to the improvements made.

The question of emulsion stability raised by Mr Lowe had been largely answered above. The method of manufacture, however, was another problem. Currently, the Department had been charged with evaluating three fundamental units: one using cavitation followed by shear, the second a maceration shear process, and the third, high pressure differentials causing subsequent cavitation and vaporization. To give further details of the devices under these circumstances would be tantamount to advertising proprietary products, but further details could be provided, if required, in private correspondence.

Jerk pump operation appeared to improve or assist with the emulsifying process and, to date, no signs of corrosion had been determined in any of the fuel injection equipment.

Mr Lowe was correct in his general assertion that emission control and fuel economy demanded separate and individual attention, and it was well known that retarding the injection sequence resulted in a measurable reduction in NO_x . However, his attention was drawn to Fig 4 where it could be seen that the application of emulsified fuels to a retarded system provided some further gain in both respects. The comments of Mr Norris-Jones tended to endorse those results, and he was to be applauded for his constructive approach to the problem of burning emulsions in diesel engine, particularly as he has acknowledged reservations. It should be noted that when Mr Norris-Jones referred to a "low" or "poor" injection build, he was alluding to almost the entire diesel engine production capacity available today, and that was where the application of emulsified fuel technology could show immediate advantages. The "good" system was that under development at Ricardo's and involved pressures exceeding 22,000 psi which obviously must improve atomization, but at a price.

Finally, the author wished to thank the contributors for their useful and helpful comments, which had undoubtedly raised the quality of the paper and the interest of the audience.

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