# Effect of Water Injection for NO$_x$ Reduction with Synthetic Liquid Fuels Containing High Fuel-Bound Nitrogen in a Gas Turbine Combustor

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*A total of five combustion tests utilizing water injection for control of NO, emissions have been conducted on three types of coal-derived liquid (CDL) fuels from the H-Coal and SRC II processes along with a shale-derived liquid (SDL) fuel supplied by the Radian Corporation. Actual testing was performed in a 0.14 m diameter gas-turbine-type combustor. For comparative purposes, each run with a synthetic liquid fuel was preceded by a baseline run utilizing No. 2 distillate oil. The effectiveness of water injection was found to decrease as the fuel-bound nitrogen (FBN) content of the synthetic liquids increased.*

INTRODUCTION

Accelerated capital requirements, more stringent emission requirements — particularly those for oxides of nitrogen (NO$_R$) — and the shortage of conventional fuels are affecting the design and use of utility gas turbines. The principal effect on capital costs has come from the requirement that the prime mover be designed to achieve the highest possible efficiency. The federal NO$_R$ emission standards, as set forth in the Federal Register (1) in 1979, limit emissions to 75 ppm(v) for stationary gas turbines with heat input 107 GJ/hr (-10,000 HP) and located in Metropolitan Statistical Areas. In some instances, the local standards are even more restrictive than those set by the Federal Government. The shortage of conventional distillate and natural gas fuels plus continued uncertainty as to their availability has prompted utilities to look to alternative domestic sources. Of particular interest are synthetic, coal-derived liquids (CDL) and shale-derived liquids (SDL).

Under the sponsorship of the Electric Power Research Institute (EPRI), Westinghouse Electric Corporation has been involved in a program (2-4) to determine the effect of burning CDL and SDL fuels in combustion turbines. In evaluating these fuels, we found that as fuel quality decreased, combustor performance also decreased, i.e. combustor liner temperatures increased along with the emissions of smoke and NO$_R$. The NO$_R$ emissions from a combustion turbine consist of thermal NO$_R$ formed in the high temperature zone of the flame by the Zeldovich mechanism (5) and fuel NO$_R$ formed from fuel-bound nitrogen (FBN)

compounds present in the fuel. The details and kinetics of FBN conversion to NO$_R$ are not fully understood. One theory is that in practical diffusion flame combustors the conversion of fuel N to NO, N2, and other nitrogen-bearing species is practically complete and occurs on a time scale comparable to that of the combustion process itself. Since CDL and SDL fuels have an FBN content that is at least an order of magnitude higher than conventional No. 2 oil, control of NO$_R$ generated by these fuels is critical if these fuels are to be used commercially.

The primary objective of the current series of tests was to investigate the effect of water injection on NO$_R$ emissions when CDL and SDL fuels are utilized at baseload conditions. The secondary objective was to ascertain the effect of water injection on other parameters, including combustion efficiency, CO, smoke, unburned hydrocarbons (UHC) and combustor wall temperature. The fuels tested were Paraho shale oil, a light H-CoalC distillate, a 3-to-1 volume blend of No. 2 oil and SRC II middle distillate, and SRC II heavy distillate. Testing was conducted on a static test rig using a 0.14m diameter combustor. Base-line data procured with No. 2 oil prior to each synthetic liquid test served as a common basis for comparison of the test data.

THE FUELS TESTED

The four fuels tested were:

- Paraho shale oil
- A 3-to-1 blend of No. 2 oil and SRC II middle distillate
- H-Coal distillate (distillation range 371 to 515K)
- SRC II heavy distillate.

The Paraho shale oil was supplied by the Radian Corporation of Pasadena, CA, and is the heavier fraction of a highly hydrogenated distillate produced by the Paraho Company and upgraded by SOHIO. The SRC II

fuels were obtained from the SRC II pilot plant at Dupont, WA, operated by the Pittsburg and Midway Coal Co. The H-Coal fuel was obtained from the Hydrocarbon Research, Inc., Process Development Unit at Trenton, NJ. Fuel analyses, presented in Table 1, were performed by the Mobil Research and Development Corporation of Paulsboro, NJ. In addition, FBN determinations were made at the Westinghouse R&D Center on three of the fuels in parallel with the water injection tests. These were done primarily to assess the effect of long-term storage on FBN content. In the case of No. 2 oil/SRC middle distillate blend, the nitrogen determination provided a quantitative measurement of the actual test fuel. FBN contents (wt %) were as follows: 0.16% (0.16%) for the H-Coal product, 0.23% (0.27%) for the blended fuel, 0.33% (0.27%) for the Paraho shale oil, and 0.94% for the SRC II heavy distillate. The values shown in the parentheses represent the Westinghouse determinations and were used for subsequent analyses in this paper. The 0.23% value for the blended fuel is based on the Mobil analysis for SRC II middle distillate adjusted for dilution with No. 2 oil containing no FBN. Note, also, that the 0.33% value reported by Mobil for shale oil was for a sample taken from a batch supplied directly to the Westinghouse Combustion Turbine Systems Division at Concordville, PA. On the other hand, the Westinghouse R&D Center sample was a 5-drum

lot from the same refinery run at SOHIO, which was shipped directly to Pittsburgh.

EXPERIMENTAL PROGRAM AND FACILITIES

Actual testing was conducted on a static test rig located at the Westinghouse R&D Center, Pittsburgh, PA. The experimental apparatus is depicted in Fig. 1 and shown schematically in Fig. 2. Air is supplied by a Fuller rotary, sliding-vane air compressor, capable of generating 1.1 kg/s of air at 709 kPa (7 atm) pressure. Air supply pressure is controlled by a pneumatic bypass valve, and flow is measured by an airflow-measuring nozzle located downstream of a pneumatically operated control valve. The air is passed through an indirectly fired heat exchanger and is preheated to a temperature of 590K, which is more representative of an actual Westinghouse gas turbine. For the water injection tests an actual airflow of 0.68 kg/s was supplied to the test section that houses the combustor (Fig. 3). The combustor itself is approximately one-half the diameter (0.14m) of the Westinghouse commercial-scale combustor and is configured to resemble it for combustion purposes. The typical airflow split in this combustor is approximately one-third for primary zone combustion, one-third for cooling, and one-third for secondary quench. The full load fuel/air ratio is approximately 0.02.

Table 1  Analytical Characterization of Fuels Tested

| Synthetic Fuel | Shale Oil 1 Paraho I | | SRC-II Heavy Distillate | | H-Coal 200-500°F | | SRC-II Medium Distillate | |
|---|---|---|---|---|---|---|---|---|
| **Physical & Chemical Properties** | | | | | | | | |
| Gravity, ° API | 310 | | 0.9 | | 30.0 | | 13.3 | |
| Pour Point. °F | 95 | | 0 | | <-65. 0 | | <-65 | |
| Flash Point. °F | 200 | | 290 | | < 75. 0 | | 169 | |
| Gross Heat of Combustion, Btu/lb | 19365 | | 17259 | | 18, 723 | | 17102 | |
| Kinematic Viscosity, cs at 40°C | 14.45 | | 31 76 | | I. 12 | | 3.20 | |
| Kinematic Viscosity, cs at 100°C | 3. 15 | | 3.45 | | 0.62 | | 1.08 | |
| Conradson Carbon Residue. wt% | 0.23 | | 0.85 | | 0.05 | | 0.17 | |
| Aromaticity,    CA | 14 | | 71 | | 34.0 | | 63 | |
| **Distillation. °F at %  ASTM Method)** | 1028871 [111] D861 | | 1028871 | 10861 | 10-28871 | 1 0-861 | 1 028871 | 1 8861 |
| IB P | 421 | 366 | 503 | 533 | 171 | 236 | 279 | 210 |
| 5 | 595 | 465 | 539 | 569 | 208 | 278 | 331 | – |
| 10 | 637 | 531 | 545 | 589 | 257 | 304 | 355 | 396 |
| 30 | 740 | 640 | 588 | 608 | 328 | 338 | 399 | 420 |
| 50 | 834 | 684 | 619 | 632 | 369 | 374 | 439 | 444 |
| M | 855 | 721 | 671 | 678 | 402 | 401 | 472 | 470 |
| 90 | 924 | 729 (at 84%1 [121] | 768 | 750 (at 86%) | 447 | 442 | 514 | 509 |
| 95 | 957 | ND | 852 | ND | 467 | 470 | 535 | 530 |
| EP | 1016 | ND | 1098 | ND | 550 | 505 | 584 | 546 |
| **Elemental Analysis. wt%** | | | | | | | | |
| Hydrogen | 12.80 | | 7. 22 | | 1138 | | 8.83 | |
| Sulfur | 0. 02 | | 0.35 | | 0.13 | | 0.21 | |
| Nitrogen | 0. 33 | | 0.94 | | 0.16 | | 0.91 | |
| Oxygen | 0. 33 | | 1.80 | | 14 | | 4.65 | |
| Ash | 0.01 | | 0.03 | | <0.01 | | <0.01 | |
| **Trace Metals, ppm wt** | | | | | | | | |
| Titanium | <0.1 | | 2.7 | | < 1.0 | | <0.1 | |
| Sodium | 1.4 | | 14.0 | | 0.43 | | 5.0 | |
| Pot,,ssium | 2.6 | | 7. 2 | | 0.06 | | 2.0 | |
| Calcium | 0.96 | | 9. 1 | | 0. 15 | | 0.52 | |
| Vanadium | 0. 12 | | 0. 23 | | 0.9 | | 0.12 | |
| Lead | 0.36 | | 0. I | | 0.2 | | 0.29 | |
| Iron | 6. 7 | | 85 | | 0. 7 | | 2.1 | |
| Phosphorus | < 0. 01 | | 0. 04 | | <0.2 | | (0.01 | |

[111]  A STM procedure modified by decreasing rate to prevent foaming.

[121]  Sample decomposed (cracked)
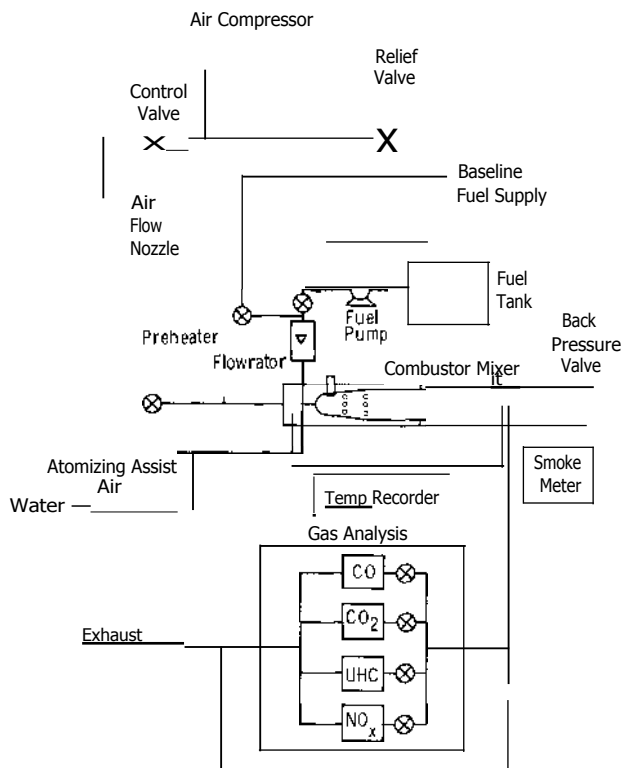
Fig. 1 Subscale test facility used

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Fig. 2 Schematic of test facility



Fig. 3 Subscale combustor used



Fig. 4 Fuel nozzle cross section

The total pressure drop is about 4% of the static pressure at full load conditions. It is equipped with six thermocouples to indicate wall temperatures.

An air-assist, pressure-atomizing fuel nozzle is used (Fig. 4). The atomizing air assist is about 1% of the total airflow at a pressure ratio of 2. In the water injection tests water is supplied along with the atomizing air through the same port. The synthetic fuel is stored in a closed 200 1 tank from which it is supplied to the combustor at 1520 kPa (15 atm) with a gear-type pump. No. 2 oil is sup- plied from a separate and larger supply tank equipped with a constant pressure fuel forwarding system. Provisions are incorporated into the fuel forwarding
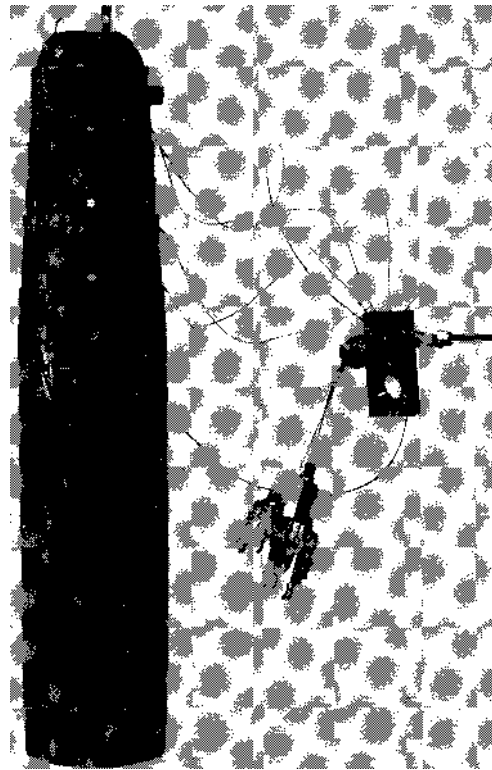
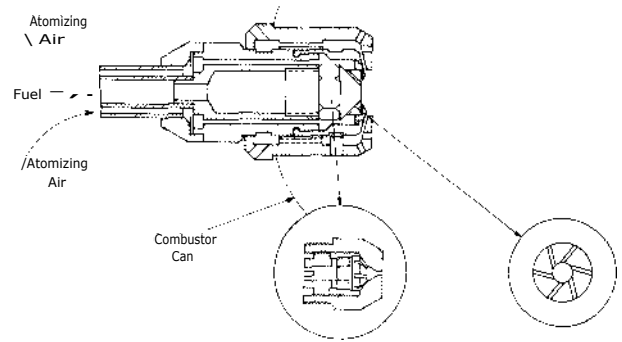system that make it possible to transfer between the two fuels without interrupting test passage operation.

Fuel flow rates are measured by a Fischer and Porter flowrator. Visual observation of the flame is accomplished through sight ports located 15 and 42 cm from the dome of the combustor. An inverted hat mixer is located at the burner exit plane, which serves to complete the mixing of the burnt products. There are eight unshielded, chromel-alumel thermocouples located in the mixer to determine the mean combustor outlet temperature. The temperatures are recorded on a Leeds and Northrup Speedomax' W recorder. There is also a gas analysis rake located in the mixer that extracts a representative sample of the combustion

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products. At the outlet of the test passage, a pneumatically operated butterfly valve is used to maintain a constant test pressure.

The exhaust gas sample is piped to the gas analysis panel through a heated line maintained at 670K. Analyzers used for the various exhaust gas species were:

| Species | Analyzer |
|---------|----------|
| $CO_2$ | Beckman Model 865 NDIR |
| CO | Beckman Model 865 NDIR |
| UHC | Beckman Model 108 FID |
| $NO_x$ | TECO Model 12A (chemiluminescent) |
| $NO_x$ | Dynasciences Model FS330 (wet cell) |

Smoke was measured by a motor-driven RDC smokemeter (made by Bacharach Instrument Co. of Pittsburgh) and conforming to ASTM D2156 standards. It was mounted adjacent to the test passage to avoid a long sampling line, thereby preserving the integrity of the sample.

The water injection tests were conducted at a nominal combustor outlet temperature of 1339K and water/fuel mass ratios varying from 0.0 to 1.2. Base-line tests with No. 2 oil (dry and with water injection) were made immediately preceding the tests for each of the CDL and SDL fuels investigated. This procedure not only provided input on the performance of the system for a given test, i.e. by comparing the base-line data of the various tests, but also enabled direct comparisons to be made between a given CDL or SDL fuel and its base line. Furthermore, these initial base-line tests with No. 2 oil, especially at low water-injection rates, were used to check the entire system for general agreement among the measured fuel/air ratio, the combustor temperature rise, and the $CO_2$ measurements. Only when the agreement was good did we proceed with the tests.

TEST RESULTS

The primary objective of the tests reported in this paper was to investigate the effect of water injection on $NO_x$ emissions for CDL and SDL fuels with high FBN contents. Testing was performed at base-load conditions. From these tests the effect of FBN concentration and water injection rate on FBN conversion to $NO_x$ could also be determined. The secondary objective was to ascertain the effect of water injection on other combustion and emission parameters along with wall temperature effects.

For our purposes, all NO measurements were corrected to set combustor inlet conditions of 590K, 405 kPa (4 atm) pressure, and zero relative humidity oxygen content existing in the exhaust gas. The correction used was of the form:

$$(NO_n)_{corr} = (NOO_{meas}) \left| EXP \left[ \frac{590 - Tin}{248} \right] \left[ \frac{4.00}{Pin,} \right]^{1.5} EXP(19H) \right. ,$$

where $Ti_n$ is the inlet temperature in K, $P_{in}$ is the pressure in atm and H is the relative humidity of the inlet air to the test passage. This equation (6,7) has been found to be of value for correcting experimental $NO$ measurements to a standard set of combustor inlet conditions in the absence of water injection. The validity of this equation under water injection

conditions, however, is only partially established for low-FBN fuels and not yet established for high-FBN fuels.

Due to the practical difficulty of obtaining the respective CDL and SDL fuels with their FBN content removed, the thermal $NO_x$ background level for these tests was determined from the base-line tests performed with No. 2 oil, which has negligible FBN. For a typical No. 2 oil with 0.008 wt % FBN, approximately 4 ppm(v) NO would be generated at 1339K, if we assume complete FBN conversion. Under the same conditions the thermal $NO$ contribution would be approximately 110 ppm(v). On this basis we have assumed in this work that the contribution of FBN to total NO is negligible for the base-line fuel. By comparison, substitution of No. 2 oil as a base-line fuel for clean CDL and SDL fuel, i.e. no FBN, has to be more significant.

The base-line corrected $NO_x$ values for all the subscale tests as a function of water/fuel mass flow for combustor exit temperatures in the range of 1270 to 1340K is shown in Fig. 5. These results are in general agreement with those predicted by Hung (8) on the basis of theoretical considerations.
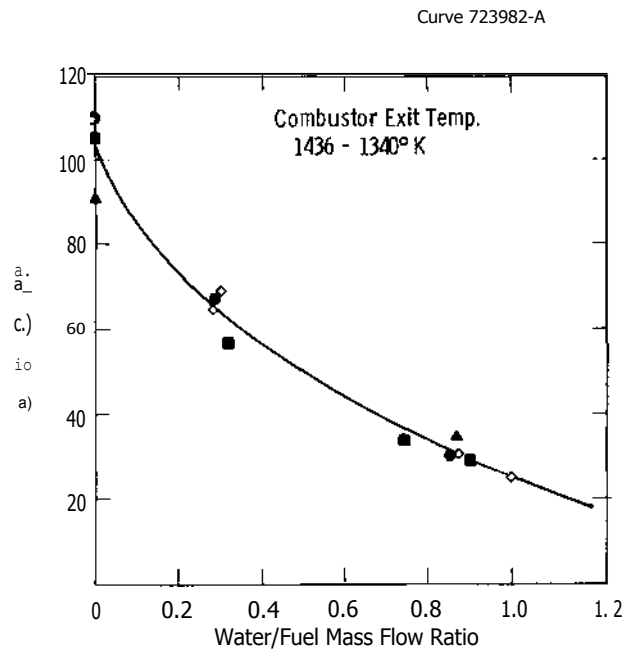
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Fig. 5 Thermal NO (corrected) emissions versus water/fuel ratio for No. 2 oil

The effect of water injection on $NO$ emissions with Paraho shale oil is shown in Figs. 6 and 7. The initial test (Fig. 6) was conducted with the shale oil heated to a temperature of 367K. At this temperature its viscosity would be similar to that of No. 2 oil and fuel forwarding would pose no serious difficulties. Under these conditions we found that a combustor exit temperature of only 1240 to 1269K could be achieved. This temperature was substantially below the desired temperature of -1339K. As a result, the test was repeated with the fuel preheat temperature increased to 395K, and sufficient fuel could be forwarded to achieve the desired combustor outlet temperature. For both tests the $NO_x$ emissions were found to be 160 ppm(v) with zero water injection and
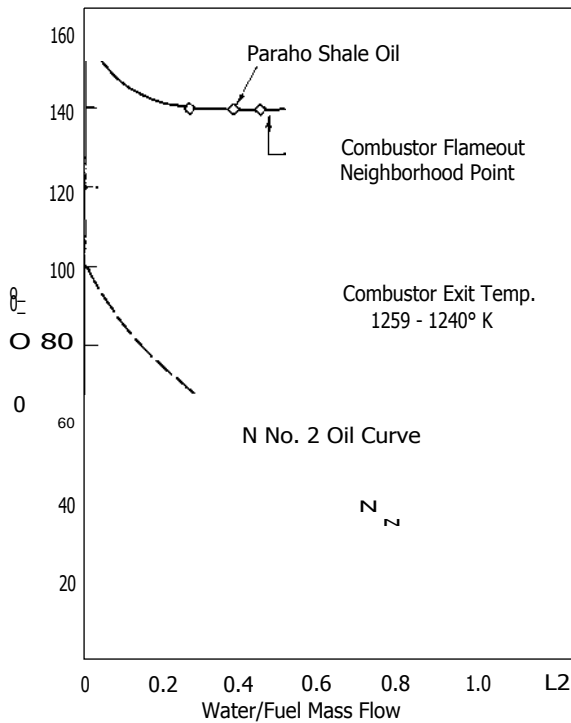
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Fig. 6 Effect of water injection on NO, emissions
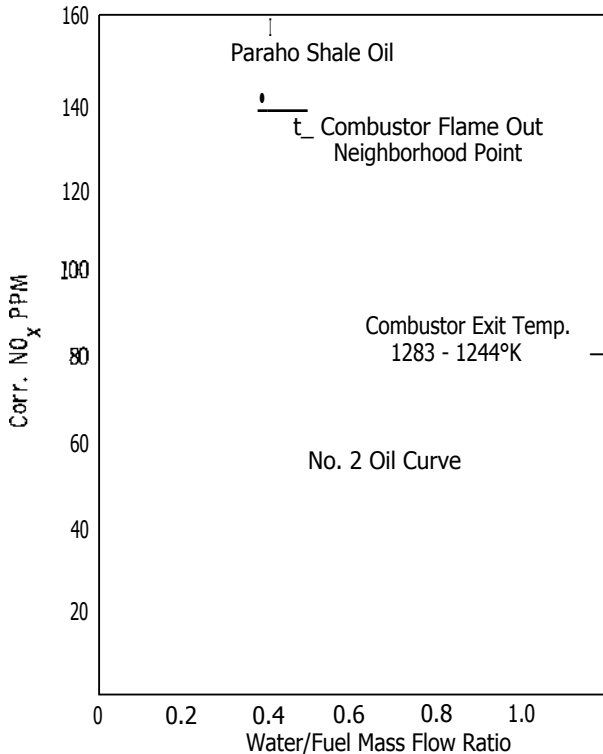for Paraho shale oil at 367K

Fig. 7 Effect of water injection on NO, emissions
for Paraho shale oil at 395K

rapidly fell to 140 ppm(v) with water injection. No
further $NO_x$ reduction was experienced for either fuel
at water/fuel ratios in excess of 0.26. Beyond this
point the combustion process became increasingly un-
stable, with flameout occurring at a water/fuel ratio
of 0.44 for the 367K preheat case and 0.48 for the
395K preheat case.

The effect of water injection on $NO_x$ emissions
using the 3-to-1 blend (by volume) of No. 2 oil and
SRC II middle distillate is shown in Fig. 8. This
method of utilizing the initially small quantities of
CDL fuels as they become available may be desirable
from a practical point of view. In this case the dry
$NO_x$ value was 180 ppm(v) and decreased progressively
with water injection. Combustor stability became
marginal at a water/fuel ratio of about 0.77, at
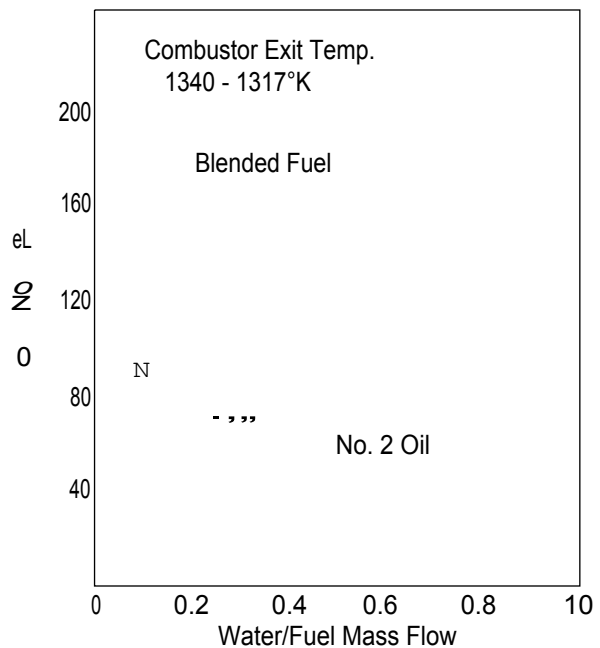which point we terminated the test.

Fig. 8 Effect of water injection on $NO_x$ emissions for
3-to-1 No. 2 oil to SRC II (middle distillate)
blend

A comparison between the dry $NO_x$ values for the
blended fuel [180 ppm(v)] and the shale oil
[160 ppm(v)] may appear somewhat surprising since
both fuels have equivalent FBN contents of 0.27 wt %.
Two factors, however, appear to be responsible for the
reduced NOx emissions observed with the shale oil.
First, the combustor outlet temperature was somewhat
lower for shale oil than for the blended fuel.
Secondly, the shale oil had a somewhat higher hydro-
gen content.

Figure 9 shows the effect of water injection on
$NO_x$ emissions when H-Coal is used. H-Coal, with the
lowest FBN of the fuels tested, had a dry NOx value
of 150 ppm(v), which decreased with increasing water
injection. We observed a minimum $NO$ value of
70 ppm(v) at a water/fuel ratio of 1.1. At this
ratio the combustor exhibited severe unstability and
appeared to be close to flameout, and we terminated
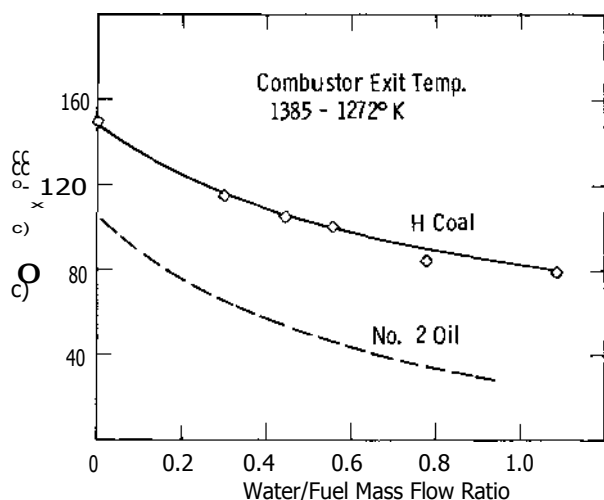the test.

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Fig. 9 Effect of water injection on NO, emissions
       for H-Coal

The water injection results obtained with SRC II heavy distillate are shown in Fig. 10. This fuel, which had the highest FBN content of the fuels tested, displayed a trend different from that of the other fuels studied. For this fuel we found that the $NO_x$ emissions increased with water injection. This trend has been predicted (8) and confirmed experimentally (9). It is based on the fact that, with high FBN fuels, the higher FBN conversion more than compensates for the reduction in thermal NO, due to water injection.
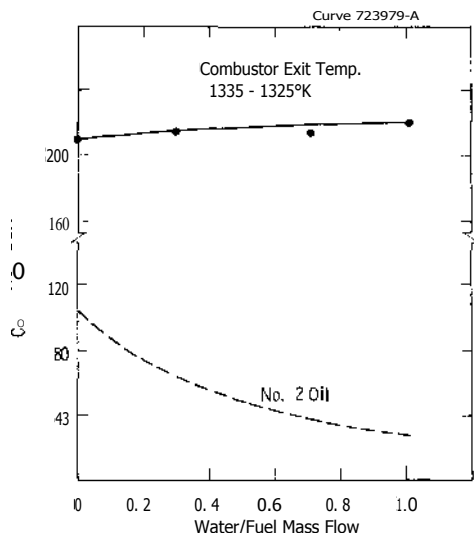
Fig. 10 Effect of water injection on $NO_x$ emissions
        for SRC II heavy distillate

Other Emissions

In addition to obtaining $NO_x$ data with water injection for the base-line and synthetic fuels, we also measured other emissions including CO, UHC, and smoke.

We noticed that as the water/fuel mass flow ratio increased, so did CO emissions. Typical CO emissions for the base-line test fuel were generally in the range of 20 to 30 ppm(v) with no water injection, rising to 500 to 1350 ppm(v) at the maximum

water injection rates, approaching a water/fuel ratio of 1. The corresponding emissions for Paraho shale oil were 26 to 32 ppm(v) rising to 400 to 550 ppm(v) at the maximum water/fuel injection rate of about 0.48. The CO emissions for the 3-to-1 blend were about 15 ppm(v) with no water injection, rising to about 600 ppm(v) at the maximum water/fuel injection rate of 0.77. For H-Coal the corresponding CO emissions were 45 ppm(v) dry, rising to 900 ppm(v) at a maximum water/fuel injection rate of 1.1. Similarly, for the SRC II heavy distillate, the CO emission dry was 16 to 17 ppm(v) and rose to 200 ppm(v) at a water/fuel ratio of about 1.0. The increase in CO emissions was insignificant until water injection was fairly large and brought the combustion process itself close to flameout. Practically speaking, this mode of operation would not be used. It is interesting to note that the effect of water injection on CO production was more pronounced with the base-line fuel. The reason for increased tolerance of the CDL and SDL fuels is not apparent at the present time. UHC emissions were fairly low at all water injection rates except the high, where combustor stability became a problem. Typically the combustor running dry gave UHC emissions in the 2 to 10 ppm(v) (of equivalent CH4), and these rose to 25 to 100 ppm(v) at the high water rates.

Water injection appeared to have no significant effect on smoke emissions, with the possible exception of the SRC II heavy distillate and its corresponding test with base-line fuel. In both cases, i.e. base-line fuel and heavy distillate, smoke numbers (ASTM D-2156) tended to increase by over 2 smoke units from a dry to maximum water injection condition. For the other base-line fuel tests, we obtained smoke numbers of approximately 4 at dry conditions, and these tended to decline with water injection by about 0.2 smoke units. With the SDL fuel we found water injection to increase smoke from a dry value of 3.8 to 4.0, but we noted no significant change due to water injection for either the H-Coal or the blend of No. 2 oil and SRC II middle distillate. Any small changes in smoke number have to be treated with caution because the scatter is approximately ±0.5 smoke units. One final point is that the high water content present in the sample in water injection runs may have tended to wet the filter paper and parts of the smoke meter. This may have resulted in some scrubbing of the smoke particles. The combustor wall temperature observed during these tests showed that water injection lowered the average (as well as the peak) wall temperatures and had a significant positive effect.

ANALYSIS OF $NO_x$ RESULTS

Fuel-Bound Nitrogen (FBN) Conversion

The problem of the interaction between FBN level and the effectiveness of water injection in a turbine combustor was first attacked by W. Hung (8) in 1976 on a semitheoretical basis. Hung assumed that FBN fully converts to $NO_x$ from the nitrogen and oxygen content of the combustion air, and therefore, the Zeldovich mechanism starts to form $NO_x$ with a finite (sometimes quite large) initial $NO_x$ level present in the gas. This initial $NO_x$ slows down the $NO_x$ formation due to the Zeldovich mechanism, though the decrease in the yield of thermal $NO_x$ is always more than counterbalanced by the initial $NO_x$ that came from FBN. Once the influence of FBN on the initiation of the Zeldovich mechanism has been established, the rest of the quantitative assessment of NO

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generation is no different from the case in which there is no initial $NO$ from FBN present. Consequently, Hung calculated the effectiveness of water injection on $NO$ reduction in the same way as is done in the case of clean fuels: the water injection causes a reduction in the flame temperature, and this effect is routinely entered in the thermal $NO$ formation calculation, regardless of whether there was or was not any initial NO, from FBN.

The FBN levels of interest in 1976 (when Hung published his findings) were low since most residual and crude oils have only a fraction of a percent FBN. While the conversion of FBN to NO, is indeed rather high (70-90%) under fuel lean conditions, as long as FBN < 0.01-0.15%, CDL and SDL liquids, however, can have up to 1% FBN; and it is apparent from more recent work (10) that 100% FBN $NO_x$ conversion cannot be assumed any longer.

Vermes, Toof and Cohn (11) showed in 1979 that retaining the 100% conversion assumption of Hung in the lean combustor zones and using a variable FBN ->- $NO_x$ conversion percentage in the fuel-rich zones of the combustor yielded a modified Hung model and gave acceptable NO correlations with experiments in dry combustors running on CDL fuels when 0.08 < FBN% < 0.69. The correlation was tested at two pressure levels in two different - though conventional - combustor geometries. A comparison of the data obtained during these tests and that calculated based on Ref. 3 shown in Fig. 11 show that large differences exist as FBN content increases. Rather than assuming a new model for the conversion of FBN to $NO_x$, we looked into the actual conversion of FBN to $NO_x$ with water injection for the various fuels from the data available.
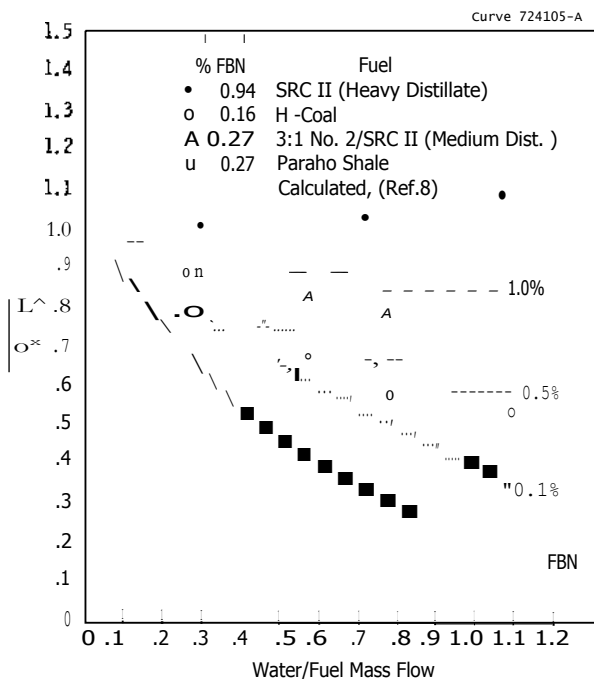


Fig. 11 Comparison of measured $NO_x$ with that calculated in Ref. 8.

It is possible to develop a correlation between conversion of FBN to $NO$ and the water injection rate for the various fuels. Conversion of fuel nitrogen to NO is defined as follows:

$\underline{Conv.}$ = Constant.

x {(conc. of nitrogen in exh. $NO$ at a given
     water injection rate)

   -(conc. of nitrogen in base-line exh. $NO_x$
      interpolated to the set water injection
      rate)

   +(mass of nitrogen in fuel)} .

As was explained earlier, the practical difficulty of obtaining the respective CDL and SDL fuels with their FBN content removed forced the use of No. 2 oil as the base-line test fuel. Thus, the first term of the numerator is derived from CDL or SDL combustion and the second from No. 2 oil combustion. The constant takes into consideration the assumed molecular weight of the exhaust gas, the air/fuel ratio, and the mass of water injected. We evaluated the test data for the conversion of FBN to NO vs water injection based on the $NO_x$ measured for the CDL or SDL fuel and the $NO_x$ value corresponding to the base-line fuel obtained from Fig. 5 for the same water/fuel ratio.' We ignored small differences in fuel flow and hydrogen content, as well as in the exhaust gas molecular weight for the test fuel and the base-line fuel.

The conversion of FBN to $NO$ with water injection is shown in Figs. 12 to 15 for the four fuels, respectively. The data are for a combustor operating at an inlet air temperature of 590K, at a pressure of 405 kPa (4 atm) and zero relative humidity, and with a combustor exit temperature of 1240 to 1340K. In all cases the conversion of fuel nitrogen to NO, increases with increasing water injection. Figure 12 is for H-Coal, which was the lowest FBN fuel tested, and Fig. 13 is for the 3-to-1 blend of No. 2 oil and SRC II (middle distillate). For both these fuels the conversion rate is fairly high at zero water injection, and the increase of conversion with water is rather small. Figure 14 is for SRC II heavy distillate. Here the conversion rate is low at zero water injection but increases rapidly with water injection. Figure 15 is for Paraho shale, which exhibited a similar trend.
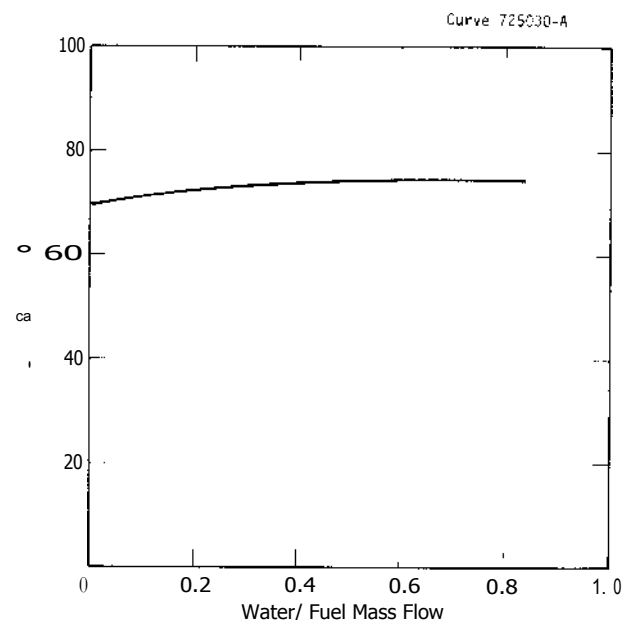


Fig. 12 Effect of water injection on FBN conversion to $NO_x$ for H-Coal
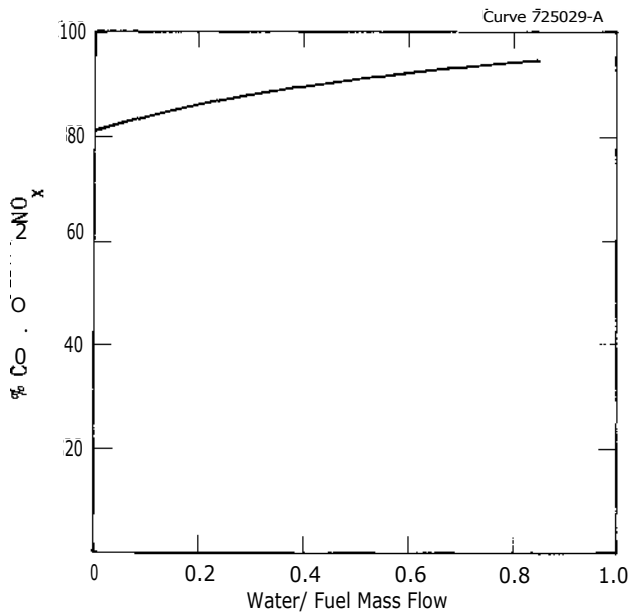
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Fig. 13 Effect of water injection on FBN conversion to $NO_x$ for No. 2 oil and SRC II (middle distillate) blend
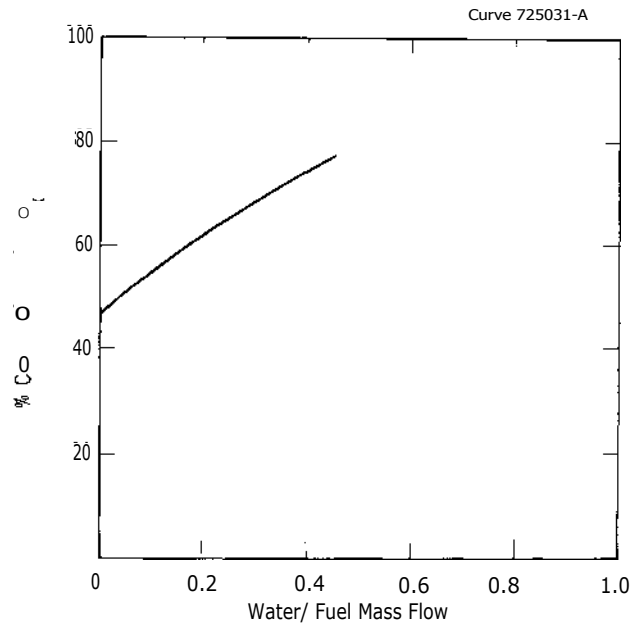


Fig. 15 Effect of water injection on FBN conversion to $NO_x$ for Paraho shale oil
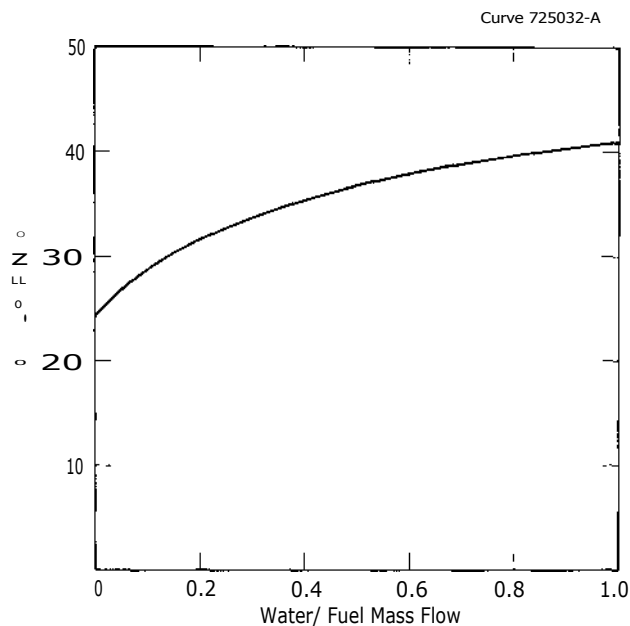


Fig. 14 Effect of water injection on FBN conversion to $NO_x$ for SRC II (heavy distillate)

The significance of these changes in the conversion of FBN to $NO_x$ with water injection is too complex to be fully comprehended in a work as brief as this. This investigation is continuing and will, we hope, lead to knowledge of those factors that influence the conversion of FBN to $NO_x$ in CDL and SDL fuels in the presence of water injection.

CONCLUSIONS

The results of these tests, in general, lead to the following conclusions:

- Fuel-bound nitrogen has a very large decreasing effect on the $NO_x$ reducing capability of water injection.

- The conversion of fuel-bound nitrogen to $NO_x$ with zero water injection and a base-load combustor exit temperature shows wide variation with the type of fuel used, being as high as 82% for the 3-to-1 volume blend of No. 2 oil and SRC II (middle distillate) and as low as 28% for the SRC II heavy distillate.

- There is an increase in conversion of fuel-bound nitrogen to $NO$ at combustor base-load exit temperatures with increasing water injection. H-Coal and the 3-to-1 volume blend of No. 2 oil and SRC II middle distillate show only relatively modest increase of conversion with increased water injection. SRC II heavy distillate and Paraho shale oil show much larger increases.

- The paraffin content of the SDL fuel may have a detrimental effect on the efficiency of water injection, namely, the freezing of fuel droplets when entering the combustor.

The above conclusions are valid for the range of the test data obtained in carrying out these tests. We made no effort to optimize the water injection configuration or to alter the combustor air distribution pattern. The combustor used had a lean front end reaction zone followed by a quick quench, a typical, conventional combustor. The fuels burned stably except at very large water injection rates, where CO emission was large and would never constitute an operating point for a turbine. Paraho shale oil was

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exceptionally difficult to handle as it had a waxy, paraffinic consistency and had to be heated to '1 373K to make it flow and atomize.

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