

Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport NO_x

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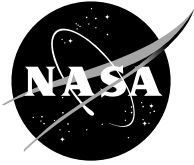
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EXECUTIVE SUMMARY

This preliminary study shows that by applying a new twist to an old water injection scheme, engine NOx emissions may be significantly reduced. In addition, the technology might offer cost savings to airlines as it could have the potential to save money on engine maintenance.

With every new engine model, pressure ratios have been climbing in the quest to improve fuel efficiency. New combustors have also been developed to help offset the exponentially higher NOx that goes with these increased pressure ratios.

The Boeing company, NASA Glenn and the Air Force Research Lab are working to study and report on how injecting finely atomized (misted) water into the engine's low pressure compressor would affect airplane and engine performance.

Water misting evaporates purified water to reduce the temperature of the engine inlet air and makes for a denser mixture. As opposed to old style water injection schemes designed for WWII through 1970's aircraft for thrust augmentation, and 30-year old commercial water injection, this "water misting" approach has additional potential benefits of improved SFC, reduced emissions and greatly reduced turbine inlet temperature. Similar technology is currently used for industrial gas turbines to increase power output and reduce NOx on hot days.

This task took a preliminary look at system design, airplane performance, maintenance, and cost implications of using the technology in aircraft for takeoff and climb-out use only. A specially designed engine performance model, or "deck", was used to evaluate the various water injection schemes. Conceptual water delivery systems were also designed for the airframe.

The study found that applying water misting prior to the LP compressor may be preferable to older direct combustion water injection systems or where water is injected into the HP compressor. If the water misting rate could be increased from a 0.83% water-to-air ratio (present industrial gas turbine rate) to about 2.2%, this could reduce NOx emissions some 47% from non-water misted engines. On cold days no SFC penalty would occur. On days above 59F, a fuel efficiency benefit of about 3.5% would be experienced. Reductions of up to 436 deg R in turbine inlet temperature were also estimated, which could lead to increased hot section life. A 0.61 db noise reduction was calculated. A nominal airplane weight penalty of less than 360 lbs. (no water) was estimated for a 305 passenger airplane. The airplane system cost is initially estimated at \$40.92 per takeoff giving an attractive NOx emissions reduction cost/benefit ratio of about \$1,663/ton.

There is a high level of uncertainty to the costs and benefits reported here, but the results are promising enough to warrant a deeper look at the possibilities this technology might offer.

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GLOSSARY

BPR	By Pass Ratio
CAEP	Committee on Aviation Environmental Protection (ICAO)
CO	Carbon Monoxide
CFR	Code of Federal Regulations (USA)
DAC	Dual Annular Combustor
EINO _x	Emissions index for NO _x given as grams of NO _x /Kg fuel
FAR	Federal Aviation Regulation (USA)
GE	General Electric
HC	Hydro-Carbons
HP	High Pressure
HPC	High Pressure Compressor
ICAO	International Civil Aviation Organization
kg	kilogram
kts	nautical miles per hour
lb	pound
Load Factor	Percentage of an airplane's seat capacity occupied by passengers
LTO	Landing Take-Off cycle
LP	Low Pressure
LPC	Low Pressure Compressor
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration (USA)
NO _x	Nitrogen Oxides
NMI	Nautical mile
OPR	Overall Pressure Ratio
OEW	Operating Empty Weight
P&W	Pratt & Whitney
PAX	passengers
SLS	Sea Level Static
std	Standard
SFC	Specific Fuel Consumption (lb. fuel per hour/ lb. thrust or power)
T3	Temperature at the exit of the HP compressor
T4	Temperature at the inlet to the high pressure turbine (TIT)
TIT	Turbine Inlet Temperature
TOGW	Take Off Gross Weight
TSFC	Thrust Specific Fuel Consumption

1.0 INTRODUCTION

This report documents the results of a NASA-funded research study to evaluate the airplane performance impacts of water injection technology.

1.1 Study Objective

Can new industrial gas turbine water injection schemes, used for NOx reduction, be used on future aircraft for cost and performance improvements?

Emissions are playing an increasingly important role in the design of commercial aircraft as well as transport military aircraft. It is important to evaluate water injection technology because absolute NOx emissions from aircraft have been difficult to control. In some cases airport NOx emissions have increased even with the introduction of newer aircraft.

In this study, preliminary costs to operators of using water injection technology for airport NOx reduction will be weighed against the cost of ever increasing emissions-based landing fees.¹ Additionally, a side benefit of water injection is to reduce engine turbine inlet temperatures. This might extend engine hot section life that could conceivably offset any costs incurred from operating the water injection system. Other maintenance issues also will be addressed in an attempt to assess the cost of the entire system.

1.2 Work Tasks

To start the study, a search was done of public and Boeing internal documents on past water injection work. Extensive writings have been published on the emissions reduction potential of this technology.^{2,3,4,5,6,7}

NASA Glenn research center conducted combustor emissions tests jointly with the Air Force Research Laboratory to establish emissions reduction potential of water misting technology. This was used in the study to estimate NOx reduction potential as well as preview the potential for HC and CO emissions increase.

NASA Glenn research center modified a NASA Engine Performance Program (NEPP) to gather overall performance estimates for injecting water before the LP compressor, between the LP and HP compressors and directly into the combustor.⁷ These performance models were verified with several performance points supplied by models from the GE Power Systems group (industrial engine) and the propulsion group at Boeing Commercial Airplanes.

The Boeing Product Development Group performed a conceptual design of the airframe water delivery system. This included design layout, weight and cost estimates for a future technology new production airplane.

Airplane performance estimates of a future technology 305 passenger airplane equipped with water injection were conducted by the Boeing aerodynamics group.

The environmental and emissions groups at Boeing provided emissions and water use estimates for the aircraft mission as well as estimated water cost, airport servicing costs and gathered airline operator feedback for using such a system.

GE, Pratt & Whitney and Rolls-Royce engine companies were all solicited to provide input and feedback on a draft report.

1.3 Potential Benefits

This technology fits with NASA's vision of improving the quality of life here on earth. Some of the benefits that may be enjoyed by the aviation community when using this technology are to:

- provide a cost effective airport NOx emissions control technology that may allow continued growth of aviation.
- may allow combustors to be optimized for cruise NOx reduction instead of compromising on a balance of cruise and takeoff reduction.
- possibly increase engine hot section life and reduce overhaul cost.
- may promote compressor cleaning to prolong engine performance which could help to reduce fuel use.
- reduce potential fuel use penalties and associated risks of other NOx control technologies, such as direct combustor water injection, or Dual Annular Combustors.

These potential benefits will be explored in the following study and weighed against the liabilities and uncertainties of the system. A high-level estimate will be given of the total system performance.

2.0 BACKGROUND

Old style water injection systems used on early Boeing 707 and 747 aircraft for thrust augmentation were unpopular with airlines because little benefit was readily seen while the drawbacks of servicing the system with water were observed every day. However, as the current drawbacks of emissions landing fees and airport restrictions overpower the need for servicing a water injection system, water injection could once again become popular.

2.1 Environmental pressures

The emissions of regulatory attention tend to be gaseous engine pollutants (e.g. NO_x, CO and HC) and increasingly, microscopic smoke particles and carbon dioxide (CO₂). International regulations make allowances for more fuel efficient, higher pressure ratio engines to emit more NO_x emissions than older engines. This is because higher NO_x emissions are typically traded off for lower HC, CO and CO₂ emissions. At the same time, airports are increasingly faced with increasing pressure to control NO_x emissions from all sources, and in some cases are facing caps from local regulatory agencies and these may start to limit some airline operations.⁸

Aviation related emissions of nitrogen oxides, which contribute to the formation of ozone, have been of particular concern to many airport operators. A federal study at 19 airports estimated that by 2010, aircraft emissions have the potential to significantly contribute to air pollution in the areas around these airports.⁹ In response to a doubling of aircraft operations from 1976 to 2000, European airports and several US local regulatory agencies are implementing emissions-based landing fees and airport emissions caps that are limiting traffic growth.¹⁰ The US military are also faced with pressures to reduce aircraft emissions and have expended emissions R&D funds equivalent to other government organizations.¹¹ Lastly, improved knowledge of health effects of emissions has led to increasing valuations in practically all emissions.¹²

2.2 NO_x

2.2.1 NO_x generation

The generation of NO_x gasses are closely linked to the engine combustor flame temperature that is in turn influenced by the Overall Pressure Ratio (OPR) of the engine's compressor. However, engines that have high pressure ratios are desirable since this tends to reduce Specific Fuel Consumption (SFC). Thus, SFC gains are often traded off against increased NO_x emissions.

During compression of air from the inlet of the engine to the inlet of the combustor, a temperature rise occurs as work is imparted to the fluid (air). The less efficient the compressor, for example 80% versus the ideal of 100%, the higher the ending temperature as shown in Figure 2.1.¹³

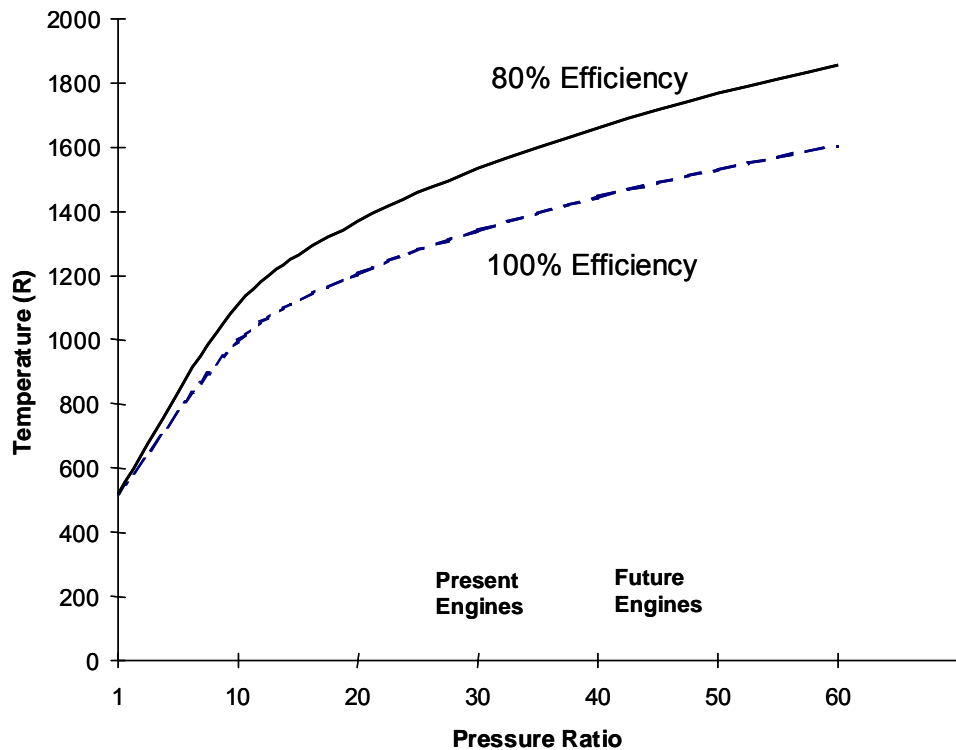


Figure 2.1. Combustor inlet temperature increases with compressor pressure ratio

After compression of the air by the compressor and introduction into the combustor, high temperatures oxidize the nitrogen in the air into oxides of nitrogen, collectively called “NOx.” This process occurs at temperatures above 1800K flame temperature and progresses rapidly as the temperature increases (film cooling on the combustor wall prevents the metal structure from melting). Combustor flame temperature generally increases with increased combustor inlet temperatures. Figure 2.2 shows the relationship of combustor inlet temperature (and hence flame temperature) to NOx formation.¹⁴

For this study, a general emissions equation was used to predict how much NOx would be generated, based on the combustor T3 and P3 conditions. This NASA equation is listed below as equation 1. A further analysis and validation of the equation, along with other equations are listed in Appendix A.¹⁵

$$E_{INOx} = 33.2 * ((P3/432.7)^{0.4}) * EXP((T3-459.67-1027.6)/349.9+(6.29-6.30)/53.2) \quad (\text{Equation 1})$$

where:

P3 = Pressure of compressor exit (psia)

T3 = Temperature of compressor exit (Deg R)

When taking into account the rise in temperature with engine pressure ratio, and the rapid rise in NOx with combustor inlet temperature, a very rapid rise in NOx occurs with small increases in pressure ratio. To see this relationship, a modern large engine (e.g. GE90 or PW4000 type of engine) performance deck was manipulated to increase OPR and observe the impact on SFC. Using the above equation to predict NOx impact, one can see in Figure 2.3 that increasing OPR results in small improvements to SFC but results in large increases in NOx.

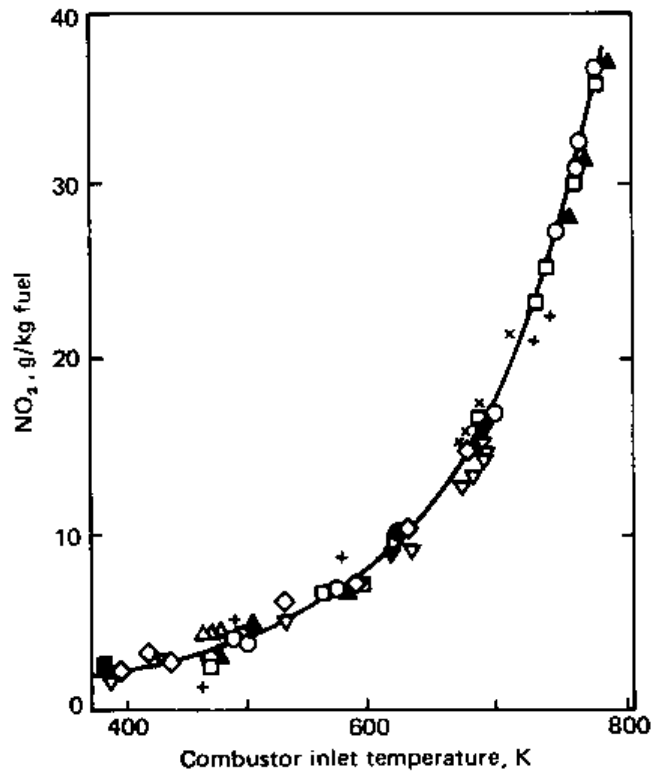


Figure 2.2. NO_x increases rapidly as combustor inlet temperature (T₃) increases¹⁴

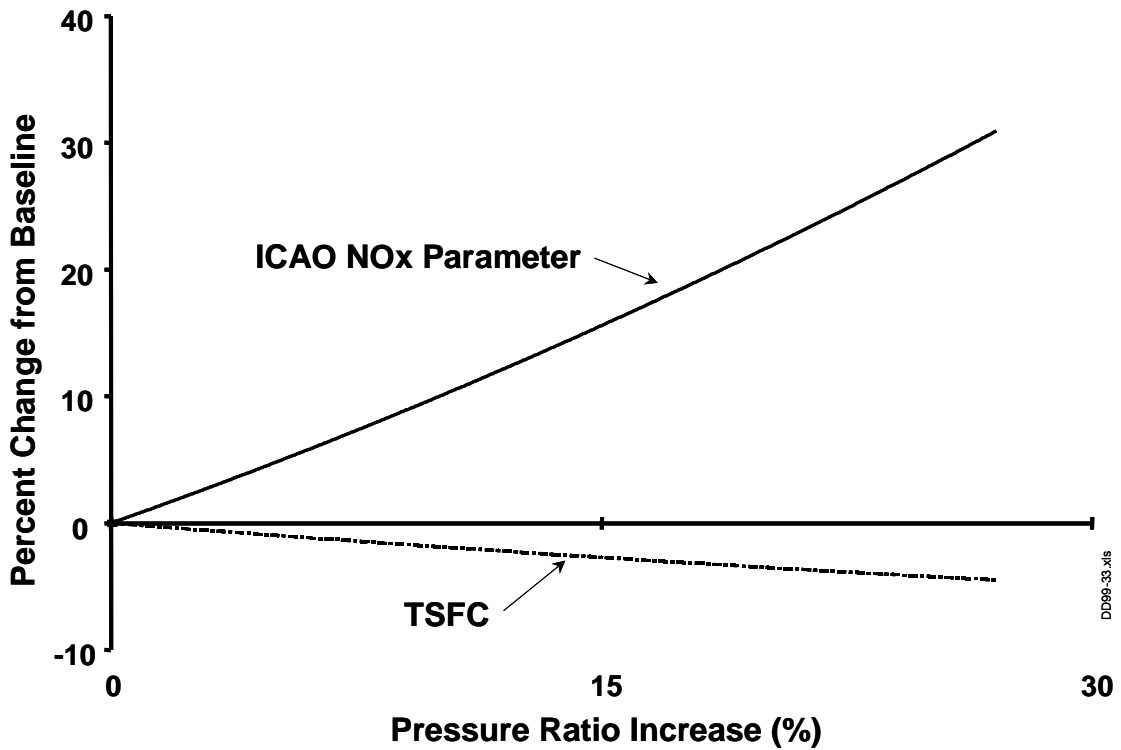


Figure 2.3. NO_x increases very rapidly for small increases in engine overall pressure ratio

2.2.2 Current NOx reduction methods

Efforts to reduce NOx emissions have resulted in research and development programs to introduce low NOx combustor technology to aero gas turbine engines. The design philosophy behind these combustors is to quickly blend the atomized fuel and air mixtures very well prior to its being burned in the combustor. As we saw in the previous section, high flame temperatures inside the combustor result in high NOx emissions. Older combustors, although efficient, stable, reliable, and often low in HC and CO emissions, had fuel/air pockets within the combustor where very hot gas generated large amounts of NOx. The combustion products then needed to be cooled via air dilution holes just prior to its leaving the combustor in order prevent the melting of the nozzle guide vanes and high pressure turbine blades. Newer combustors, such as the one shown in Figure 2.4, mix the air and fuel very well in the dome of the combustor to achieve a more homogenous mixture, thereby eliminating the hot pockets within the combustor. Since the flame temperature is more accurately controlled, and overall is cooler, the dilution holes are eliminated. The introduction of these low NOx combustors is vital to help control emissions over the entire range of the aircraft.¹⁶

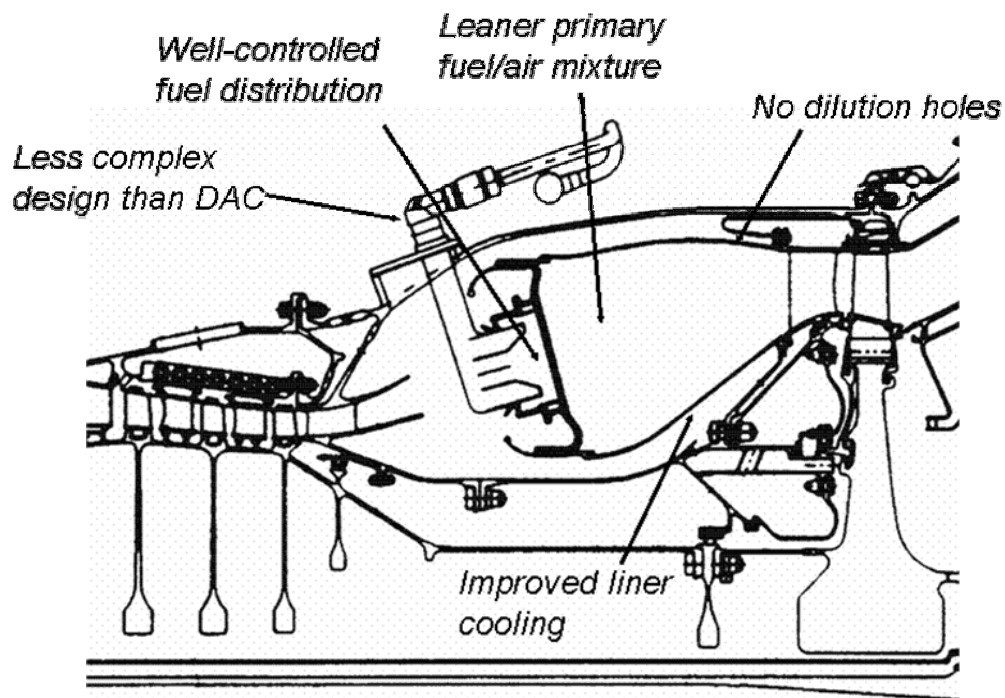


Figure 2.4. New GE TAPS combustor technology is reducing NOx formation

Although the new combustor technology is capable of reducing NOx emissions, it generally arrives just in time to be introduced into a new engine with an even higher OPR. Often the new combustor only offsets the additional NOx that would have been generated by the higher OPR. Continued development of advanced combustor concepts are needed for cruise NOx emissions reduction and renewed investigation of other concepts such as water injection for takeoff emissions reduction.

Since high fuel efficiency turbine engines are very desirable, the focus in the aviation community has been on increasing OPR for newer engines. Without the use of improved low emissions combustors, NOx emissions would have climbed exponentially. However, by introducing these new technology combustors into the new, higher OPR engines, NOx emissions have been kept in check. Figure 2.5 shows these OPR and NOx performance trends for small commercial aircraft over time. This story is similar for other aircraft categories. As a result, little progress has been achieved in reducing airport NOx emissions because the focus has been on reducing fuel use (i.e. CO₂) emissions and operator cost.

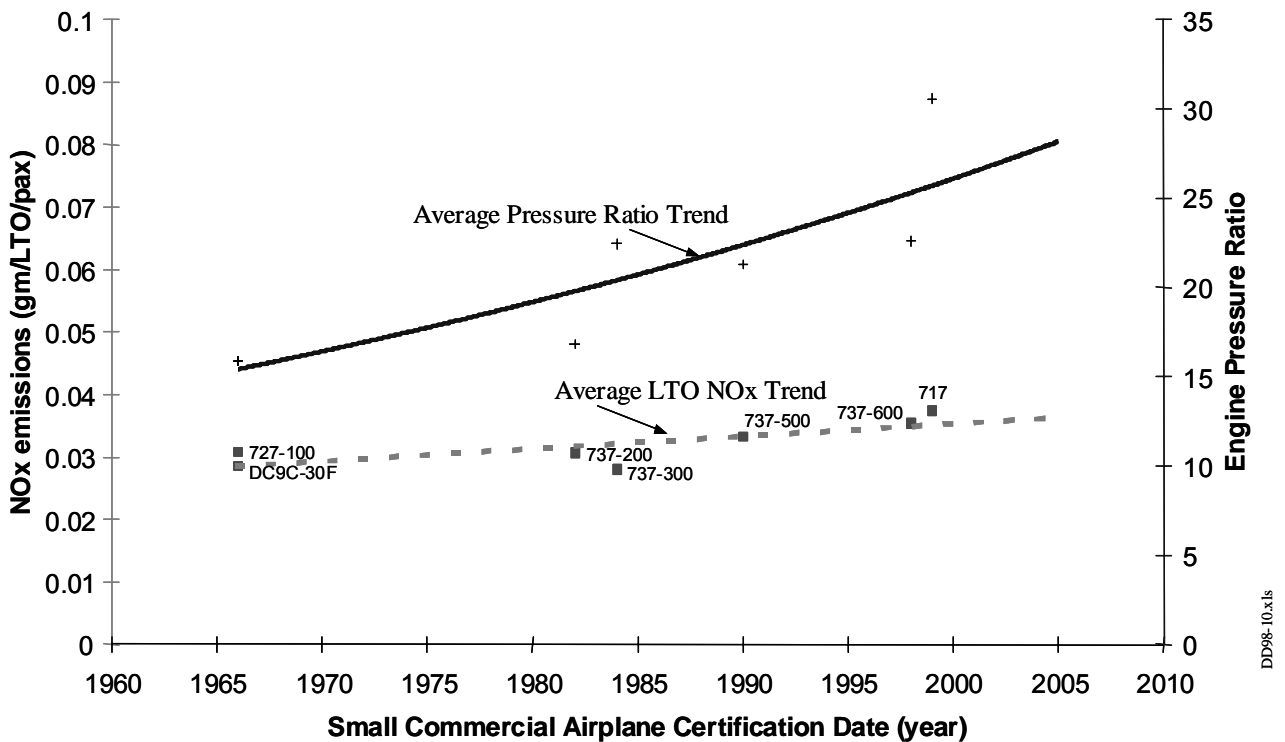


Figure 2.5. Increasing OPR trends have delineated NOx progress

2.2.3 NOx at airport

Although effort is under way to establish NOx emissions regulations for cruise, all current regulations are intended to constrain emissions in the airport vicinity.

Airplanes are typically the largest contributors to airport NOx. A representative comparison of emissions type and mode is shown in Figure 2.6.¹⁷ By halving airplane NOx emissions, other modes of transportation (i.e. car) could conceivably overtake airplanes as the major emissions contributor.

The standard method of calculating airport emissions for aircraft is the Landing Take Off (LTO) cycle¹⁸ as shown in Figure 2.7. Established times in modes are set for each operating condition (idle, taxi, takeoff and approach). The fuel flow (kg. /min.) and emissions index (grams of emission per kg of fuel consumed) at each operating condition is measured during the certification process of the engine model. Summing up these values and dividing by the engine's Sea Level Static (SLS) takeoff thrust produces a result titled "Dp/Foo". This is used in evaluating the emissions vs the regulatory standards.

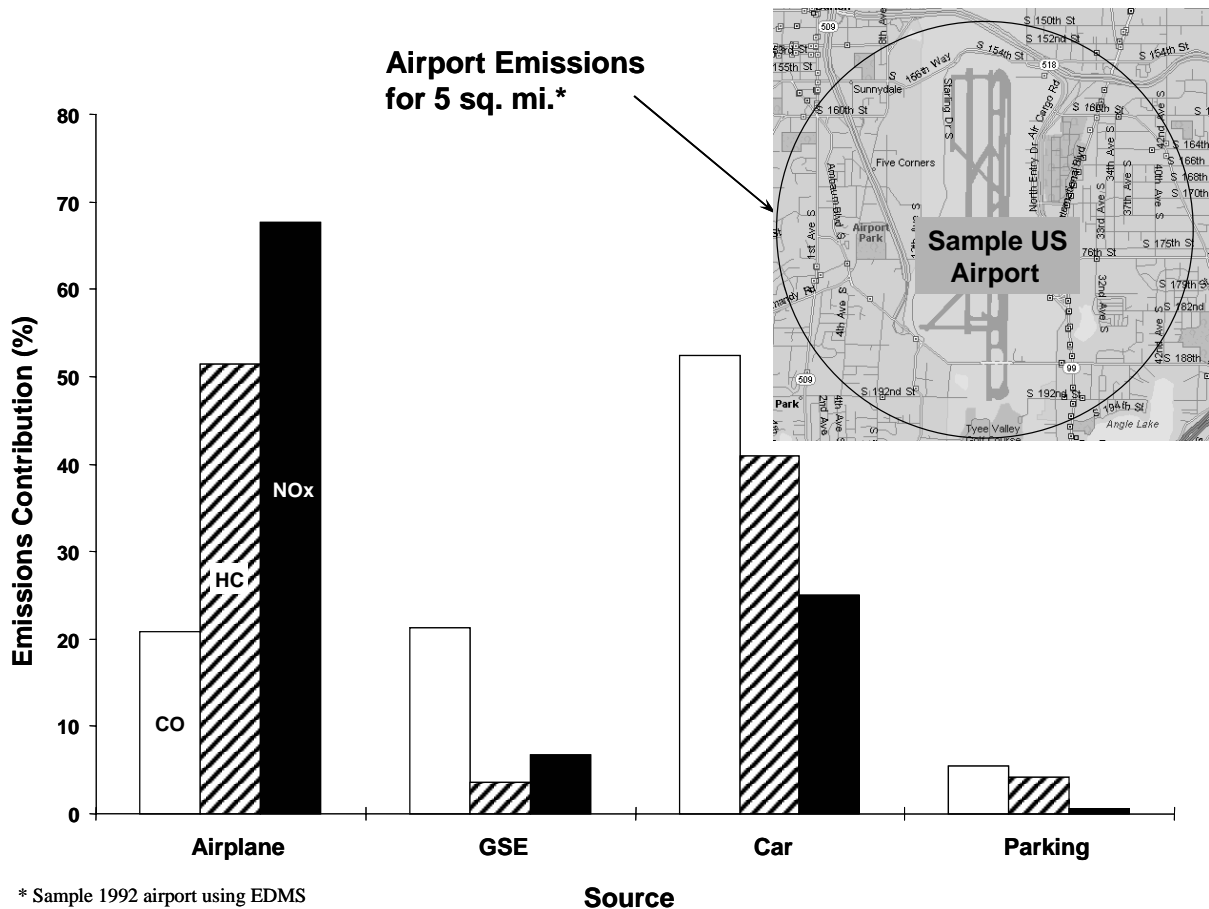
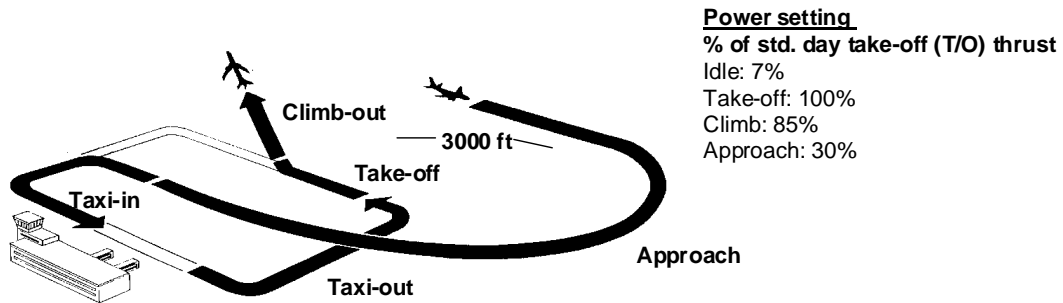


Figure 2.6. NOx is the airplane emission of focus at airports



Operating mode	Time	Fuel Flow	EI	Dp/Foo
1. Taxi / idle	26.0 minutes	• x.x kg/min	• x.x g/kg fuel	= x.x g/kN
2. Take-off	0.7 minutes	• x.x kg/min	• x.x g/kg fuel	= x.x g/kN
3. Climb	2.2 minutes	• x.x kg/min	• x.x g/kg fuel	= x.x g/kN
4. Approach	4.0 minutes	• x.x kg/min	• x.x g/kg fuel	= x.x g/kN
				Sum ÷ T/OThrust = Ave. Dp/Foo

Figure 2.7. Landing Take Off (LTO) is used to measure airport emissions

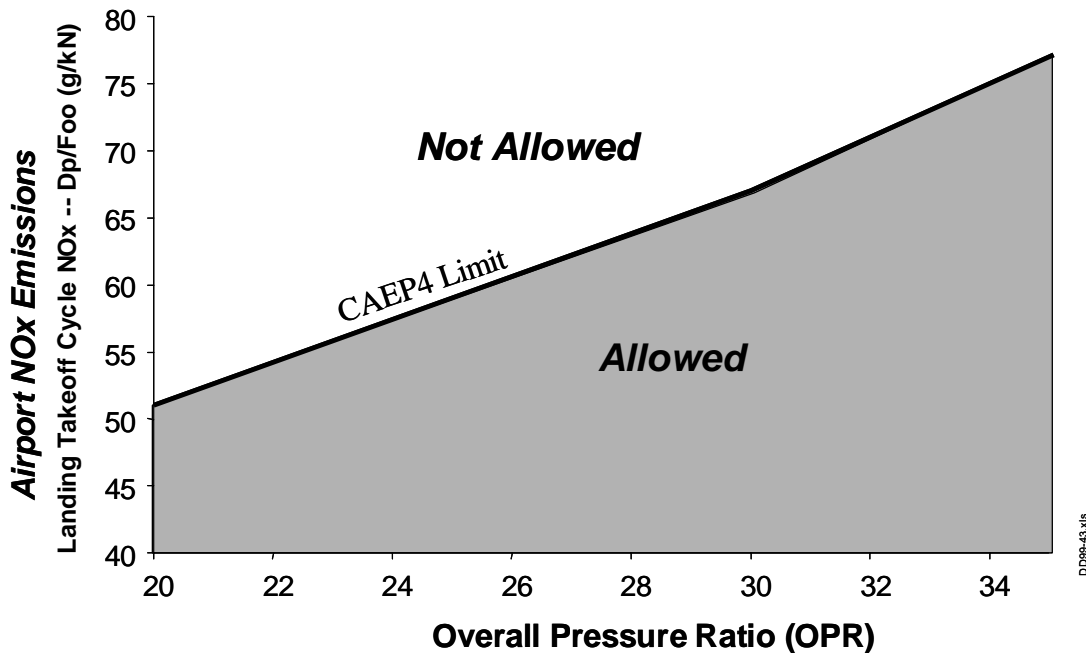


Figure 2.8. Higher OPR engines are allowed to emit more NOx

As will be discussed in the next section, NOx emissions tend to increase dramatically with increases in the engine's OPR. Recognizing this relationship, and taking into account that higher OPR engines typically exhibit better fuel efficiency, the ICAO regulatory agency has made allowances for high OPR engines to emit higher NOx emissions. This is shown in Figure 2.8.

2.3 Water Injection System Descriptions

Water injection has been used for over 30 years in industrial engines to reduce NOx emissions. It has also been used for over 45 year in Boeing's 707 and

747 aircraft engines to augment thrust some 10-30%.¹⁹ However, water injection has not been used on aircraft to reduce emissions. As gas turbine engines have matured and became capable of generating ever more thrust, water injection for new engines has been abandoned. However, there are still a few aircraft in service that continue to use water injection.²⁰

2.3.1 Traditional engine water injection system

2.3.1.1 Original Pratt & Whitney aircraft systems – At Boeing, water injection was first used over 45 years ago on Pratt & Whitney JT3C-6 engines. These engines were installed on early Boeing 707-120 Stratoliner aircraft and the water injection system augmented takeoff thrust (Figure 2.9). As the water was injected into the engine inlet, it cooled the air by evaporation and provided a 35% thrust increase on a 90F day. On days below 40F, water was injected into the HPC diffuser only which still provided a slight increase in thrust. However, as the ambient temperature dropped below 22F, no thrust increase could be achieved from water injection.

This system used a belly tank to store the demineralized water and an electrically driven boost pump delivered water to the 4 engines. At that point, an engine-driven mechanical pump then increased the pressure to about 400 PSI for injection. The engine pumps were known for generating pressure surges and oscillations which were later corrected through several service bulletins.

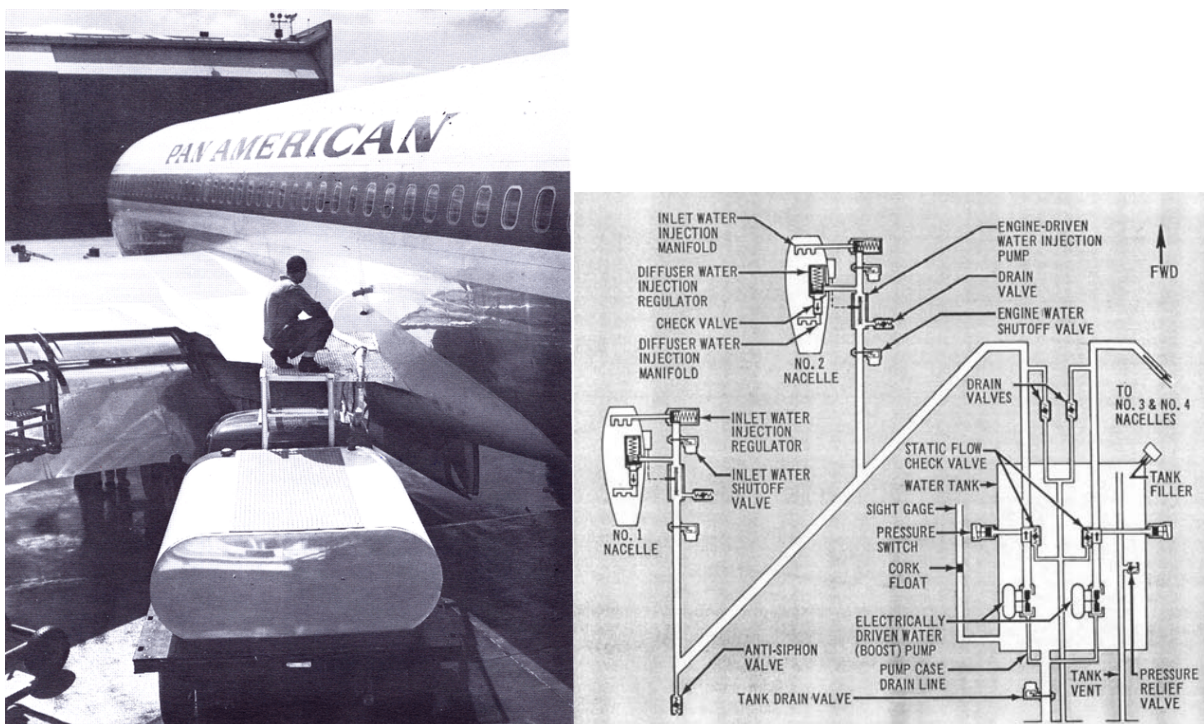


Figure 2.9. First Boeing use of water injection was for early 707 aircraft.

The last water injection system to be used on Boeing aircraft was for the early 747-100 and 747-200 aircraft using Pratt & Whitney JT9D-3AW and -7AW series engines. In this application, water was injected into the compressor discharge air stream via spray bars located just up stream of the combustor and downstream of the HP compressor as shown in Figure 2.10.

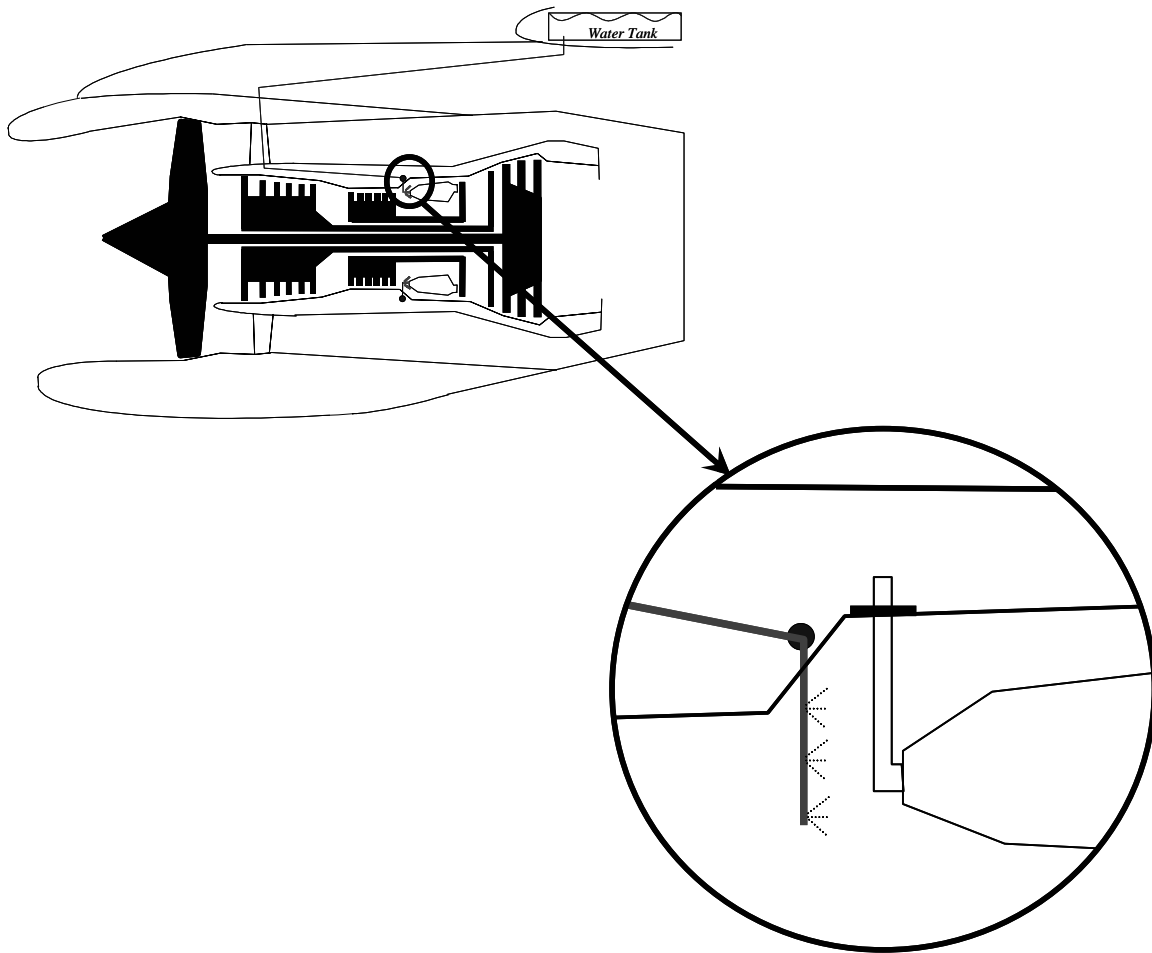


Figure 2.10. Water was injected prior to the combustor via spray bars on early Boeing 747 aircraft engines.

Water was supplied to these spray bars from a water manifold that was run next to the fuel manifolds and is shown in the figure below.

The design of this system suggested that the water distribution was not as well controlled as in later industrial water injection systems. This would lead to some portions of the combustor receiving more water which would lead to poor temperature pattern factors for the HP turbine. Thermal stressing of the case and surrounding metal structures was also reported on such systems, presumably due to the sudden introduction of the cool water which then impinged on the hot metal surfaces.

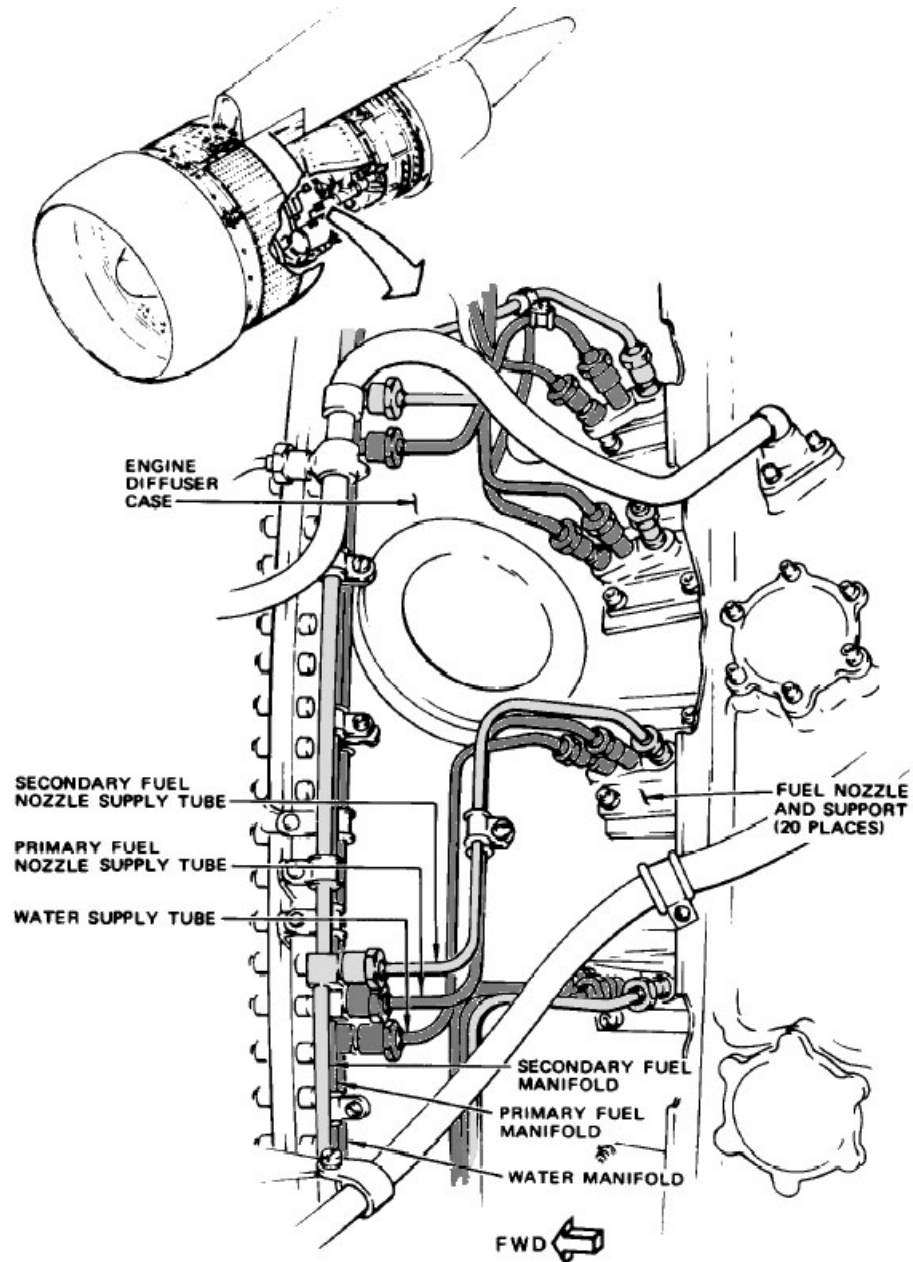


Figure 2.11. Manifolds supply water to the injection spraybars in older 747 aircraft engines.

2.3.1.2 Common industrial combustor injection systems – On later industrial engines, the improved water injection technique was to spray water directly into the combustor dome (Figure 2.12) via a dual fuel/water nozzle as shown in Figure 2.13.

By atomizing the fuel and water together inside the combustor, a better distribution of water could be maintained as compared to the previous system (2.3.1.1), and so the combustor exit thermal pattern factor was restored to acceptable levels. It also eliminated the thermal stressing on the case since water was now only directed to where it was needed ... inside the combustor.

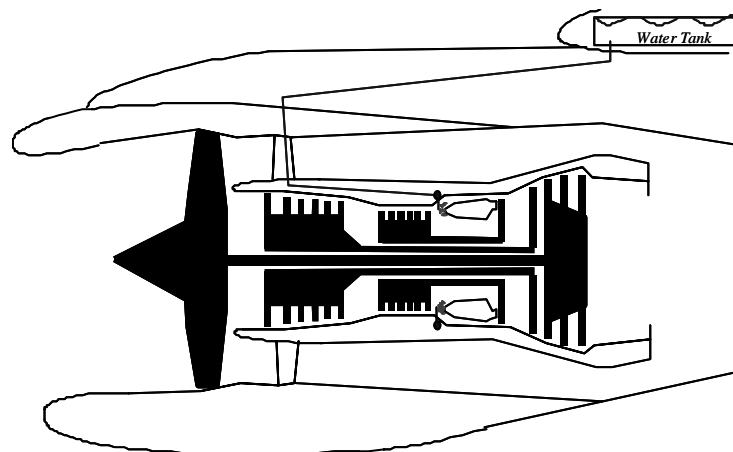


Figure 2.12. Traditional Industrial-type water injection system illustrated on an aircraft engine.

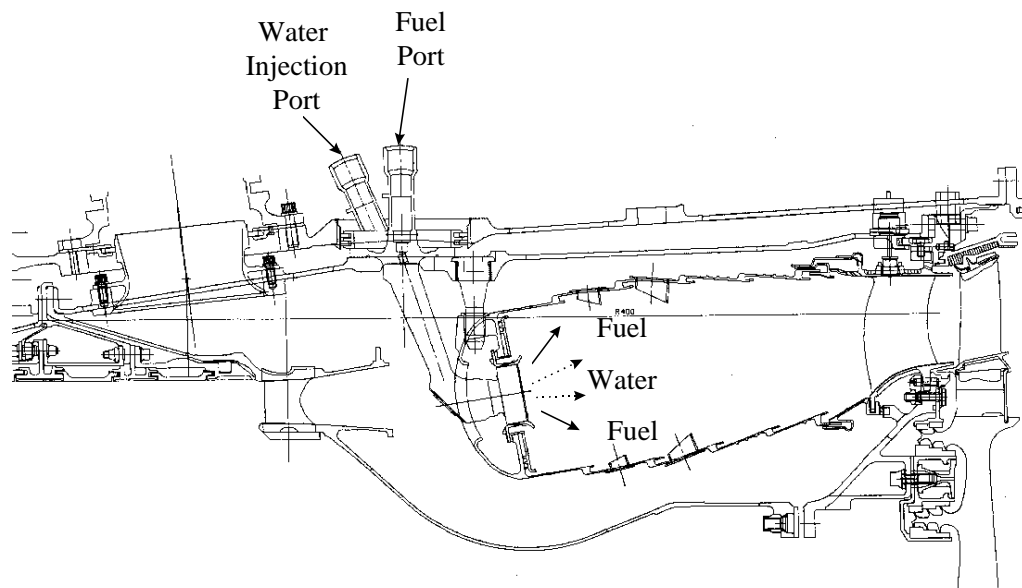


Figure 2.13. Traditional industrial systems inject water directly into the combustor

Other newer methods of injecting water involve the injection of steam through a special dual port fuel nozzle. However, the injection of water is preferable over steam as it is more effective in reducing NOx emissions. Since steam injection requires a larger volume, an especially good optimization of the flow conditions are required.²¹ Due to its size and steam generating requirements, steam injection is not an option for airborne applications.

2.3.2 Compressor water misting system

2.3.2.1 Description – The maximum power that an engine develops is largely determined by volume (i.e. mass) and the incremental velocity (i.e. acceleration) of the airflow moving through the engine.²² When water is sprayed into the compressor inlet, the temperature of the compressor inlet air is reduced and consequently the air density and thrust are increased.^{23,24}

With the evaporation of the water droplets, and the corresponding drop in air temperature, the combustor inlet temperature also drops. This reduces NOx formation. In addition, as the engine thrust has now been increased by increasing the mass flow, the engine throttle can be reduced to keep the same level of thrust as before water misting. This decrease in throttle setting also lowers the combustor inlet temperature. This results in a further drop in NOx formation.

Figure 2.14 shows the water misting system with an injection point before the LP compressor and also before the HP compressor. Typically, 24 air-assisted spray nozzles inject the water from the front frame of the engine.⁴⁶ In addition, water can also be injected between the LP and HP compressors. The LP compressor injection system would no doubt be discontinued during very cold atmospheric conditions to prevent the water from freezing. In the Figure below, high pressure air from the HP compressor exit could be used to further atomize the water injection points.

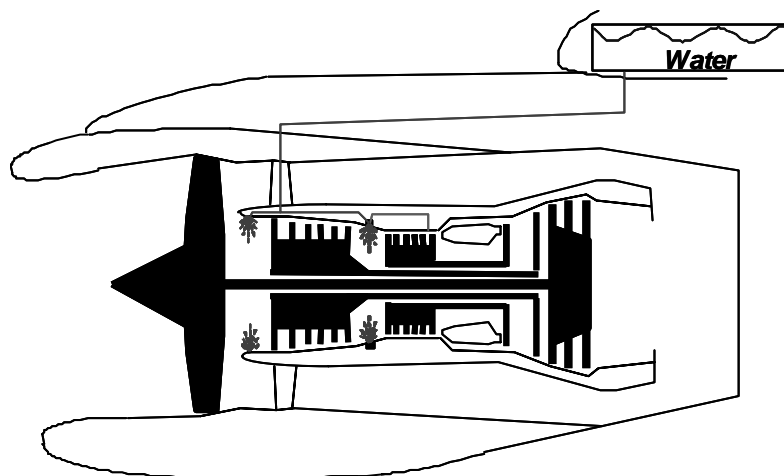


Figure 2.14. Water misting intercooler system sprays water into LP and/or HP compressor with HPC air to assist in water atomization

2.3.2.2 Operability Concerns – Depending on the location that water is introduced into the engine, the low pressure compressor and high pressure compressor can have different operating impacts, either moving towards or away from the compressor surge line. Figure 2.15²⁵ shows that for both LP and HP compressor, injection of water into the HP compressor diffuser, (up stream of the combustor) will result in the compressor moving towards the surge line. However, when introducing water into the inlet of the LP compressor, this will cause the HP compressor to move towards the surge line and the LP compressor to move away from the surge line.

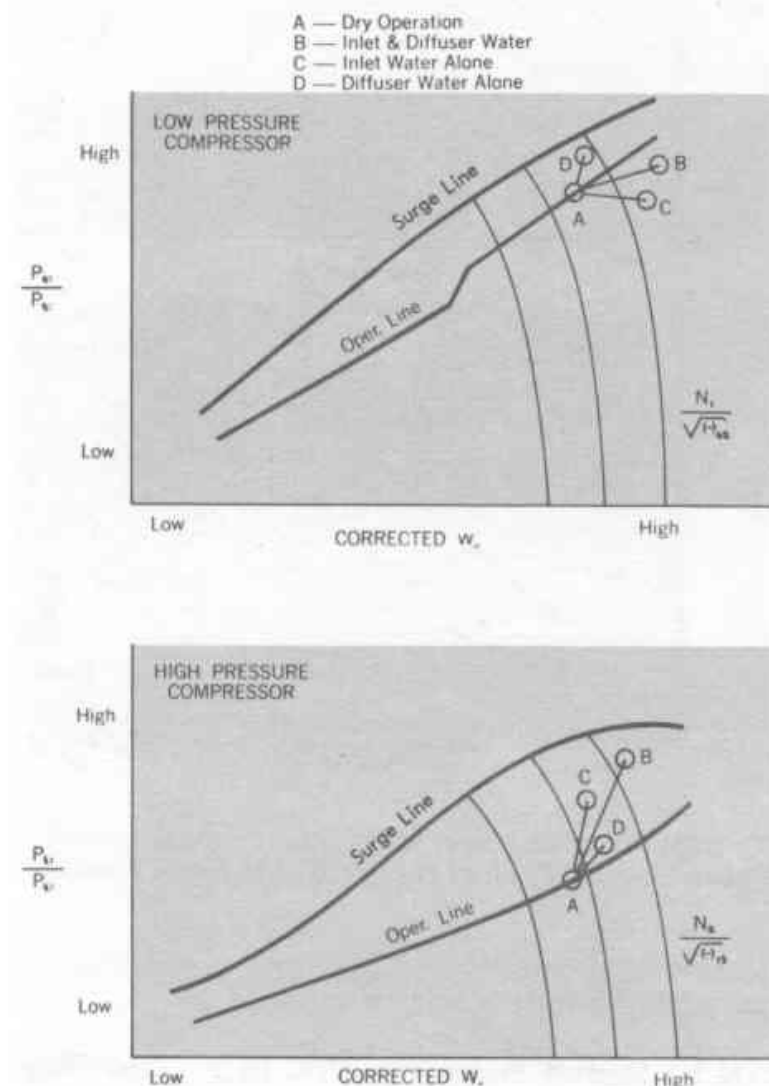


Figure 2.15. LPC water injection can move compressor away from surge line²⁷

The amount of water, the state of the water (evaporated or liquid phase) and the ambient air conditions will all have an impact on whether the LP compressor moves towards or away from the surge line. A more in-depth analysis is required to evaluate how the LP and HP compressors will behave with the amount of water required to achieve the NOx reduction goal. Once the impact is understood, the engine could be designed to operate with these increased or decreased surge margins. The re-designed compressor's performance and weight impact could then be taken into account for an overall airplane-level performance assessment.

2.3.3 Traditional water injection, airframe system

The original system used on the 747-100 and -200 airplanes used four electrically driven (400 Hz, 115/200 VAC, 3 ϕ , 36 KVA) high pressure (534-750 psig), high volume (26K-30K pph) centrifugal pumps to inject water directly into the diffuser section (upstream of the combustion chambers) of the JT9D engines. The pumps are mounted to water storage tanks fitted with bladders in the wing center section forward dry bay of 747-100 series airplane, or in a storage tank in the inboard leading edge of a 747-200 airplane as shown in Figures 2.16,²⁶ 2.17 and 2.18. All tanks are equipped with fill, drain and quantity indicating systems.

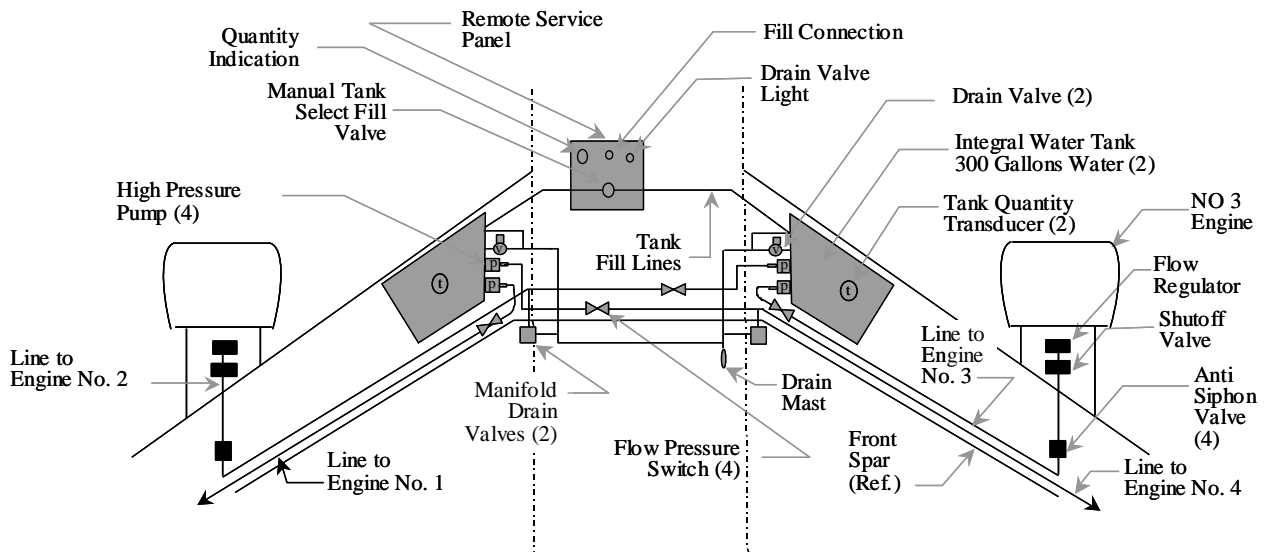


Figure 2.16. 747-200 airframe water injection system is well-proven²⁸

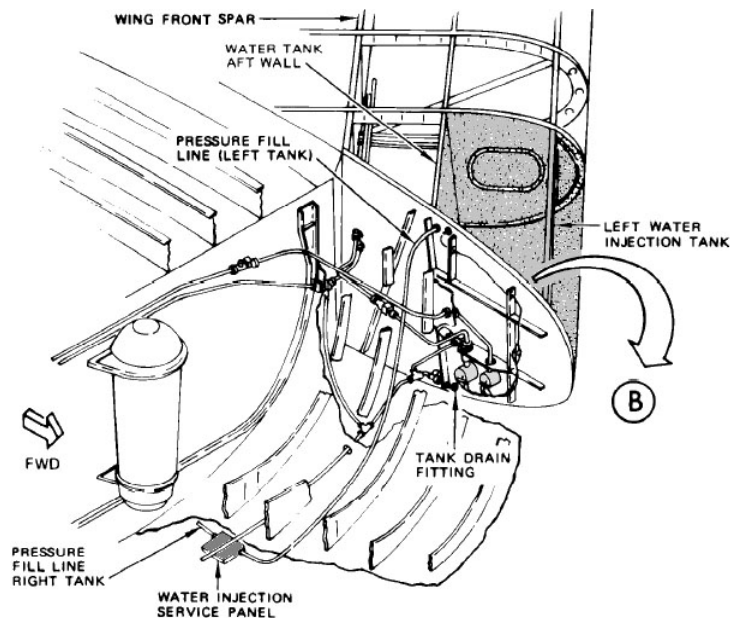


Figure 2.17. 747 water injection system used dry bays in the wings to avoid displacing any fuel capacity.

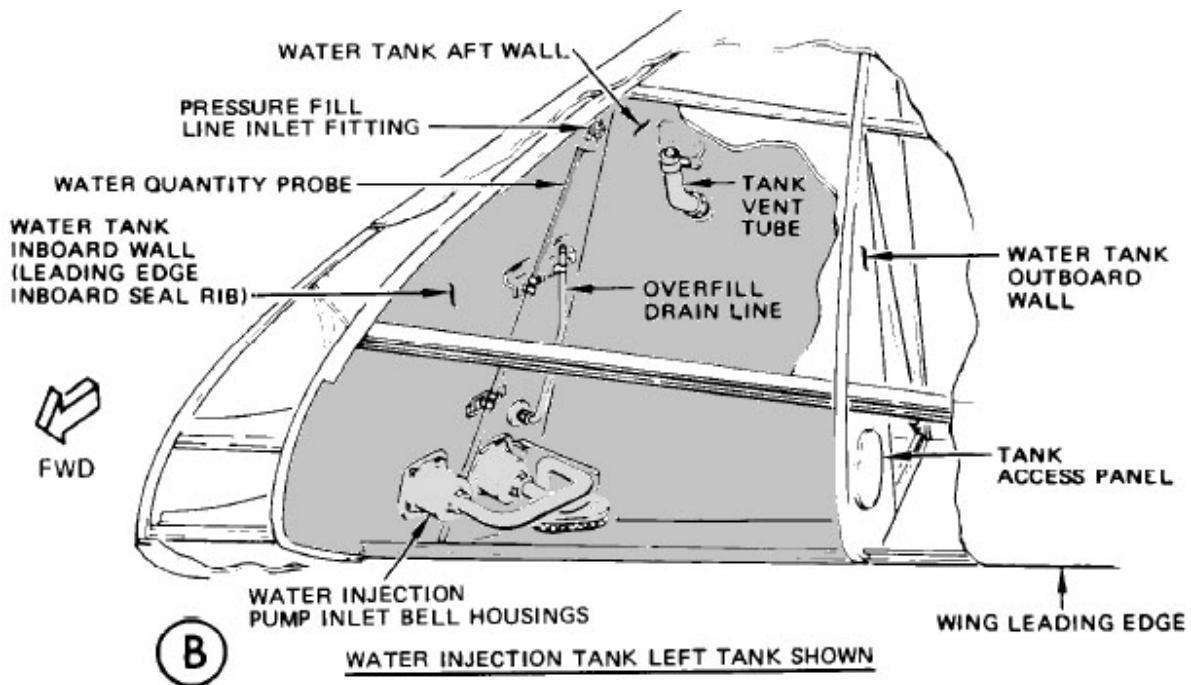


Figure 2.18. Installation of water injection tanks in aircraft is a proven technology

A water injection switch in the cockpit is turned on just before takeoff to activate the water pumps. As the engine throttles are advanced past 92°, compressor discharge air will energize the shut off valves and water will flow to the engines.

When the water is exhausted (about 2 ½ minutes later), a low water pressure switch will notify the flight crew and also send a signal to the engine fuel control unit to reduce the fuel flow (and thrust) to normal dry rate to avoid burning up the turbine section. The flight engineer should then turn the water injection switch off and turn the “drain valve” switch on. This will drain any remaining water in the tanks, and lines (about 20 gallons) overboard through a heated drain mast in approximately 8.5 minutes.

For refill operation, the tanks are connected to a 30 psig external water line where it will take 5.6 minutes to refill the tanks with 600 gallons of purified water.

The system could operate at temperatures down to 0°F.

2.4 Commercialization issues of NOx reduction technologies

2.4.1 Maintenance, Reliability and Operability

Maintenance of low emissions systems must also be included in evaluating the cost of such systems as this may detract substantially from the cost effectiveness of the emissions control device, and in some cases turn an apparently attractive technology into an unpalatable one.²⁷

Several water injection airframe system anomalies were found on the earlier 747-100 series aircraft that were later corrected through service bulletins. These included shutoff valve, water flow regulator, reset check valve, anti-siphon valve, drain mast reactivation, and installation of 20 micron water filters.²⁸ Other reported problems were related to leaking fittings.

Another design issue for the airframe system is the requirement to design such a system as to prevent the mixing of water and fuel in the separate tanks. In 1973, a BAC 111 aircraft crashed after takeoff at Hamburg Germany because fuel had inadvertently been put into the water tank.²⁹ Design of unique filling nozzles should help solve this problem.

For aero engines, turbine blade erosion was identified on early Pratt & Whitney JT9D-3AW engines, but was corrected on later engines by introduction of high-strength, nickel alloy turbine blades.²⁹ Other hot section problems occurred by not using de-mineralized water. This has ruined engines which would then require a complete overhaul.³⁰

On early industrial engines while using water injection continuously, shortened hot section life was reported for engines using the direct combustor injection systems.⁵⁴ In some cases, combustor life was reduced from the typical 16,000-24,000 hours to as short as 3,000-8,000 hours. Shortened fuel nozzle life was also reported. As the components failed, this led to the failure of the turbine blades, requiring the engines to be overhauled at substantial cost. As these issues have

now been addressed, engine reliability has increased and no adverse impacts on engine hot section life or durability have been uncovered.⁵¹

On later industrial engines, using the GE Sprint system of continuously injecting water into the LP compressor for power augmentation, metal erosion has been discovered on the first three rows of the compressor blades.³¹ However, for use in aero engines during the short time span of takeoff, this should not cause a problem.

With the old water injection system on 747 aircraft with JT9D engines where water was injected in the HP compressor diffuser prior to the combustor (see section 2.3.2.1), P&W states that there were water leaks issues, case distortion, combustor and turbine erosion, performance deterioration from hole plugging, coating erosion and tip clearance problems with the old system. Pattern factor was also affected. Lastly, water injection into the combustor was preferred over LP compressor injection due to compressor erosion problems.³² These aspects need to be examined further for the water misting intercooler approach.

The compressor blade erosion problem, both reported by GE and P&W, when injecting water into the LP compressor needs to be further investigated. If the compressor blades are experiencing erosion when water injection is used continuously, then perhaps there may be some opportunity for cleaning of the blades when water injection is used only intermittently during takeoff.

On Naval gas turbine engines that had water injection with large water manifolds, engine flameouts were reported during rapid emergency deceleration from full power to idle conditions.³³ However, this problem was reported to be solvable by altering the engine control laws but would likely need much further investigation to examine the much more critical operating envelope for aero engine applications.

From Boeing maintenance data of TWA aircraft using water injection on 747 aircraft, and from previous 707 aircraft water injection maintenance data, reported maintenance for the water injection system was \$6,865 in 1975 dollars as shown in table 2.1 below. Calculated current costs are updated by using the consumer price index.³⁴

Table 2.1. Historical and Current Maintenance Costs

<u>Airplane</u>	<u>Maint. Cost</u>	<u># takeoffs</u>	<u>Cost per takeoff</u>
Reported 747	\$6,865	828	\$8.29 (1975 dollars) \$20.62 (2003 dollars)

Water freezing in the lower part of the water tanks and pumps was reported on early 747-100 aircraft. No permanent damage was reported and the faulty valve or switch that prevented water from being used or drained was replaced and the system put back into service.

On freezing days, it was reported that water should not be loaded onto the airplane prior to 1 hour before departure.²⁸ Presumably, the relatively high temperature of the water kept the system from freezing. On older aircraft (e.g. WWII airplanes), water was often mixed with alcohol to prevent freezing on cold days. This could also be an option for new commercial aircraft that do not use engine bleed air for passenger cabin pressurization as no alcohol or water vapor would have a path into the passenger cabin. The alcohol would only be consumed in the combustor so there would be no additional cabin or airport environmental issues to consider.

2.4.2 New Engine/Airplane Introduction

For this study, we consider the introduction of the technology to be on newly designed future commercial airplanes and engines. This traditionally tends to be the most economical way to introduce new technologies. In addition, when introducing new technology, the aircraft can be designed to take advantage of any performance opportunities. This will lead to a further enhancement of the technology by designing the airframe specifically to the task, multiplying the benefit which can lead up to a further 50% improvement over the original technology improvement.¹⁷

For military applications, large cargo aircraft might consider the technology, but it would be impractical for combat/tactical aircraft.³⁵

2.4.3 Retrofit

Past studies have shown that retrofitting existing aircraft tends to be much more expensive than the original technology designed into new airplanes.⁴⁰ As water injection technology is a very integral system in the engine, it is cost prohibitive to remove existing aircraft engines and modify them for water injection. Today, many engines do not routinely undergo complete overhaul at which time might provide an opportunity to replace existing components with those designed for water injection. Instead, the engines health and component integrity are monitored and those modules replaced when needed. Thus, some engines can stay on wing until the end of the airplane's life.³⁶

2.4.4 Previous water injection studies -- lessons learned

In 1973, the U.S. EPA promulgated strict emissions control requirements for aircraft engines.³⁷ As low emissions combustor development was still in its infancy, alternate means for emissions reduction were sought after. Thus, a cost/benefit study was conducted to evaluate conventional airplane combustor water injection systems.³⁸ Often, choosing challenging ground rules of a study can adversely affect the study results. In this case, the study chose to include water injection for

the APU.³⁹ This was a noble effort as APUs can also contribute measurable amounts of NO_x in the airport environment.⁴⁰ However, this design ended up severely penalizing the overall airplane performance. For future studies, the lessons learned from this earlier endeavor would be to:

1) Eliminate the APU water injection system, reducing total aircraft system weight some 25%

2) Do not carry water to the destination for use in water injection during descent, taxi-in and gate arrival, saving some 750 lb on a 747-sized aircraft.

3) Evaluate keeping the engine's water-to-fuel injection ratio at or below a 0.5:1 ratio to prevent large increases in HC and CO. This also reduces the NO_x reduction effectiveness somewhat, but overall system performance will most likely improve.

4) Utilize the dry bays in the aircraft wings (see section 2.3.4) for water storage to avoid having to construct special water tanks in the cargo area, saving some 50% on the remaining system weight.

5) Utilize improved engine water injection schemes (such as water misting injection) to avoid the large SFC penalties estimated for the previous study. The SFC penalty is typically 3% for modern combustor water injection systems and will probably reduce substantially for the water misting intercooler system. The older Pratt & Whitney style water injection system in the study was estimated to contribute a 10% SFC penalty.

3.0 STUDY METHOD

3.1 Process

Historical combustor and engine test data was gathered and compared to more recent tests⁴¹ of advanced combustors. These data were used to first establish a correlation between the water injection rate and NOx reduction rate.⁴² Ratios of water to air and water to fuel were calculated and used to predict the amount of NOx reduction possible for a modern commercial aircraft engine.

Engine performance decks from Boeing (EDASA), GE power systems and NASA Glenn (NEPP) were used to estimate the performance impact of injecting water into the engine. These decks were each run with similar fuel, air, water and power rates to validate that they were providing similar answers. The NASA deck was then run with water injection rates higher than was possible for the Boeing and GE decks, setting out to achieve a 50% NOx reduction goal. The NOx reduction amount was compared to the historical data and found to agree fairly close.

For the now established water injection rate, the airframe systems and water tanks were designed to inject enough water for a 777-sized aircraft to takeoff and reach 3,000 feet altitude before exhausting the water supply. The increased available thrust was not used in takeoff since the aircraft should be designed for fail safe operation of the water misting system (in the event of a single engine failure or other critical episode where additional thrust is needed, the water misting or injection system could enhance safety margin.) Weights, costs and airplane performance data were then generated.

The change in airplane performance was estimated from the engine deck data (e.g. SFC change during takeoff) and the airframe design changes (e.g. increased weight of the system causing higher fuel use.) Airplane performance sensitivities were used to calculate the change in mission length and fuel use.

Water costs were estimated from historical data as well as input obtained from water conditioning companies. Airport infrastructure issues were estimated from internal data and consultation with a major airport operator (Seattle-Tacoma International).

Customer input was gathered from questionnaires sent to major air carriers to assess the desirability of the water misting intercooler system.

Particular study emphasis was placed on the water misting intercooler system as previous engine company studies highlighted many negative aspects of conventional water injection systems (e.g. SFC penalty, pattern factor).^{31, 32}

3.2 Airplane and Engine Model

3.2.1 Airplane Type

The airplane used for the study was a conceptual 777-200ER aircraft with a new composite wing sized to be used with a current technology GE90 series engine as shown in Figure 3.1. This aircraft was previously configured for a NASA Langley study of 21st century wing technology⁴³ and had a Gross Take Off Weight of about 636,500 lb.

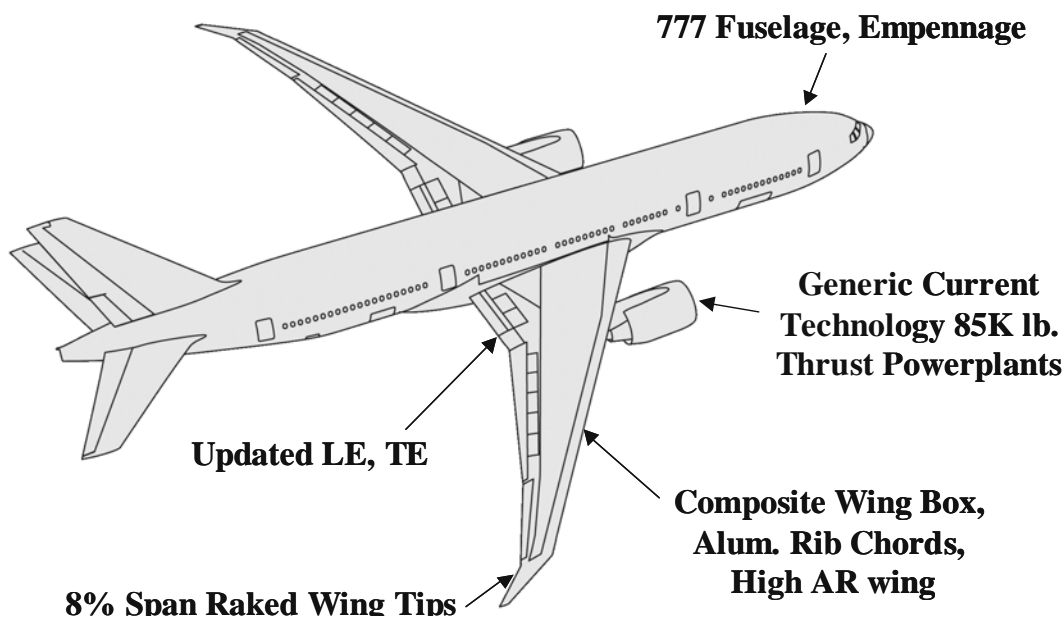


Figure 3.1. Advanced technology 777-type study airplane used for baseline

3.2.2 Engine Types

Two engine types were used in the study, an aero-derivative industrial gas turbine engine and an aero engine.

3.2.2.1 Industrial Engine Model – The GE aero derivative engine, model LM6000 was used in the study to compare performance with aero engines. This is a 40MW class engine that operates both with and without the Sprint water misting intercooler system where water is atomized and sprayed into the compressor.

3.2.2.2 Aero Engine Model – A generic, current technology, large bypass ratio Numerical Engine Performance Program (NEPP), similar to the PW4000 and GE90 series engines, was used by NASA Glenn and Boeing in the final performance analysis of the aero engines so that no proprietary engine company data would be disclosed. GE90-85B and PW4084 engine performance models were used internally by Boeing to validate the results of the NASA performance analysis.

4.0 RESULTS

The impact of water injection on engine performance is evaluated for an industrial engine using a performance program where atomized water is injected into the LP compressor. In addition, water injection impact was also evaluated for an aero engine where water is injected directly into the combustor, before the engine inlet, into the LP compressor, into the HP compressor and a combination of LP and HP compressor water injection.

A preliminary airframe system was designed and airplane performance was estimated using aerodynamic performance modeling tools.

4.1 Industrial Engine Performance

For a GE power systems LM6000 industrial engine, the following data was estimated using their engine performance models. This Sprint water misting intercooler system injects atomized water before the LP compressor.

4.1.1 Increased Power

The water misting system used on the industrial engine is primarily intended to boost output power on hot days. It does this by lowering the turbine inlet temperature (T4), which allows increased fuel flow, bringing the power back up to cool-day conditions. Thus, a constant T4 temperature is maintained as ambient temperature increases. As shown in Figure 4.1., at a temperature of 90F, a 20% increase in power is achieved when water is injected at a rate of 0.87% water to air mass flow ratio into the engine core. This drops to a 5% increase at 59F for an injection rate of 0.53%. Below 45F, power increases are negligible.⁴⁴ Even when power is increased, the SFC (Btu/kW-hr, LHV), NOx emissions and compressor exit temperatures (T3) all decrease.

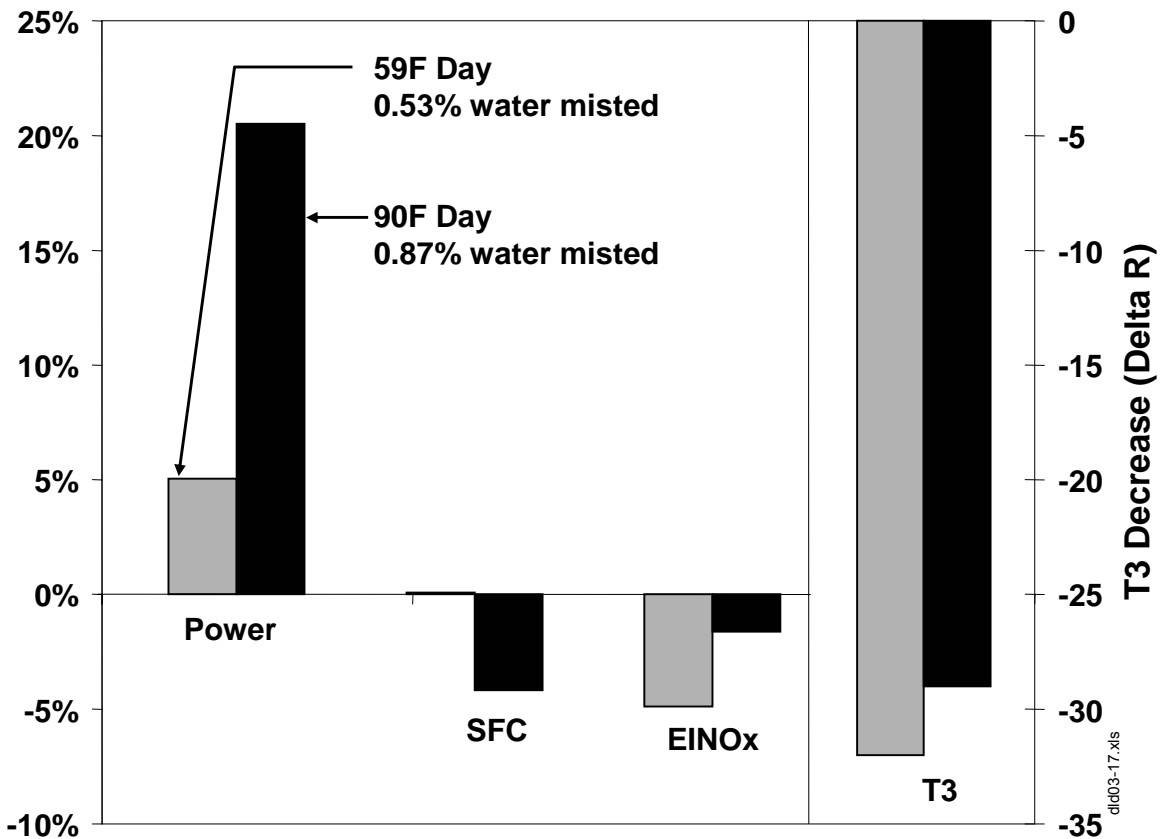


Figure 4.1. Injecting water into LP compressor on an industrial engine during warm days increases power while reducing NOx, T3 and SFC (Btu/kW-hr)

4.1.2 Same Power, Reduced NOx

The above condition in 4.1.1 assumed that power was increased by increasing water flow rate and T4 was maintained. When maintaining a constant power setting, and letting T4 fluctuate, it is anticipated that the T3, EINOx and SFC will further improve. However, as the LPC water misting system on the industrial engine was designed only to improve power output, the engine performance models were unable to run this condition.

The same power, reduced NOx scenario is the same as will be considered for the following aero engine evaluation. Namely, engine power will not be increased beyond the normal rated engine output, but water injection will instead be used to reduce NOx and the fallout effects of SFC and T4 will be observed.

4.2 Aero Engine Performance

The aero engine performance effects will be evaluated by varying the method of water injection (e.g. inlet, LPC, HPC and combustor). The inlet and LPC injection methods should reflect similar trends as the industrial engine.

4.2.1 Engine Inlet Injection

The first water injection scheme will involve injection of water at the inlet of the engine. This method is not considered to be feasible for current aircraft engines due to the significant amounts of water required (largest part of water would exit through fan and not affect engine core). However, using the Boeing engine performance deck to validate the industrial engine performance trends is of interest.

Air input conditions to the Boeing engine performance deck were manipulated to simulate water misting, with complete evaporation, into the inlet of the engine. This was done by specifying air temperature and humidity conditions. For example, the psychrometric chart in Figure 4.2 shows two conditions ... a 100F, 20% relative humidity condition and a 69F, 100% relative humidity condition. If an engine were run at the 100F point, and water was introduced and completely evaporated in the inlet, the temperature would drop to 69F with a corresponding increase in relative humidity.²⁶ Extracting the specific humidity numbers from the graph below, one will find a 0.71% water to air ratio increase.

$$\frac{110 \text{ grams} - 60 \text{ grams}}{7005 \text{ grams} / \text{lb}} \cdot 100 = 0.71 \%$$

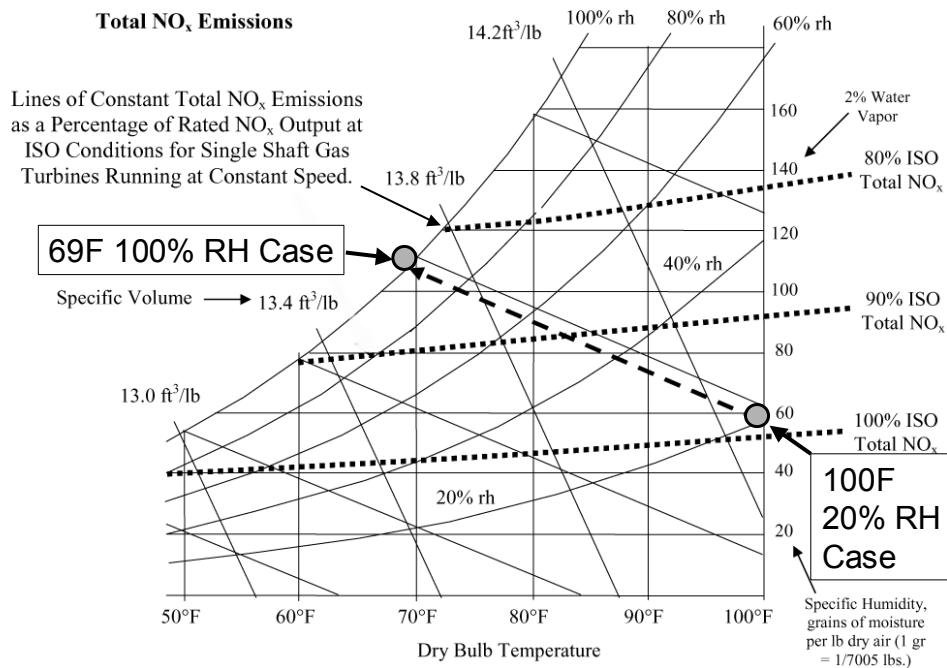


Figure 4.2. Evaporating water will reduce air temperature from 100F to 69F and increase relative humidity from 20% to 100%²⁶

The engine performance impact on these two operating conditions can be seen in Figure 4.3. By injecting 0.71% water to air ratio and keeping the engine throttle setting unchanged (i.e. take off power setting or PS=50), the thrust increases 7.7% and SFC increases 0.76%. NOx decreases 14.9% and T3 decreases 43R. When increasing the aircraft speed to the point of lift off (i.e. 0.25 Mach), the thrust further increases 9.07% more than the non-water misted engine. SFC decreases 0.56% while NOx and T3 remain essentially unchanged from the static condition.

This shows that water misting the engine inlet improves thrust, T3 and NOx emissions. Next, since the study is only considering using water misting for NOx reduction and not power increases, the throttle setting of the engine will be reduced while water misting to keep the same thrust level as without water misting. Figure 4.4 now compares the previous data point of the 0.25 Mach condition (constant throttle setting) to that of a reduced throttle setting, keeping the same thrust output as the non-water misted condition.

Figure 4.4 shows that when the engine throttle is retarded to keep the same thrust output (at 0.25 Mach) as without water misting, further improvements in SFC, T3, T4 and NOx emissions are gained as compared to keeping the throttle setting constant. When using a 0.71% water misting rate on a 100F day with 20% RH, the engine's SFC improves 3.25%, T3 decreases 88R, T4 decreases 163R and NOx decreases 28%.

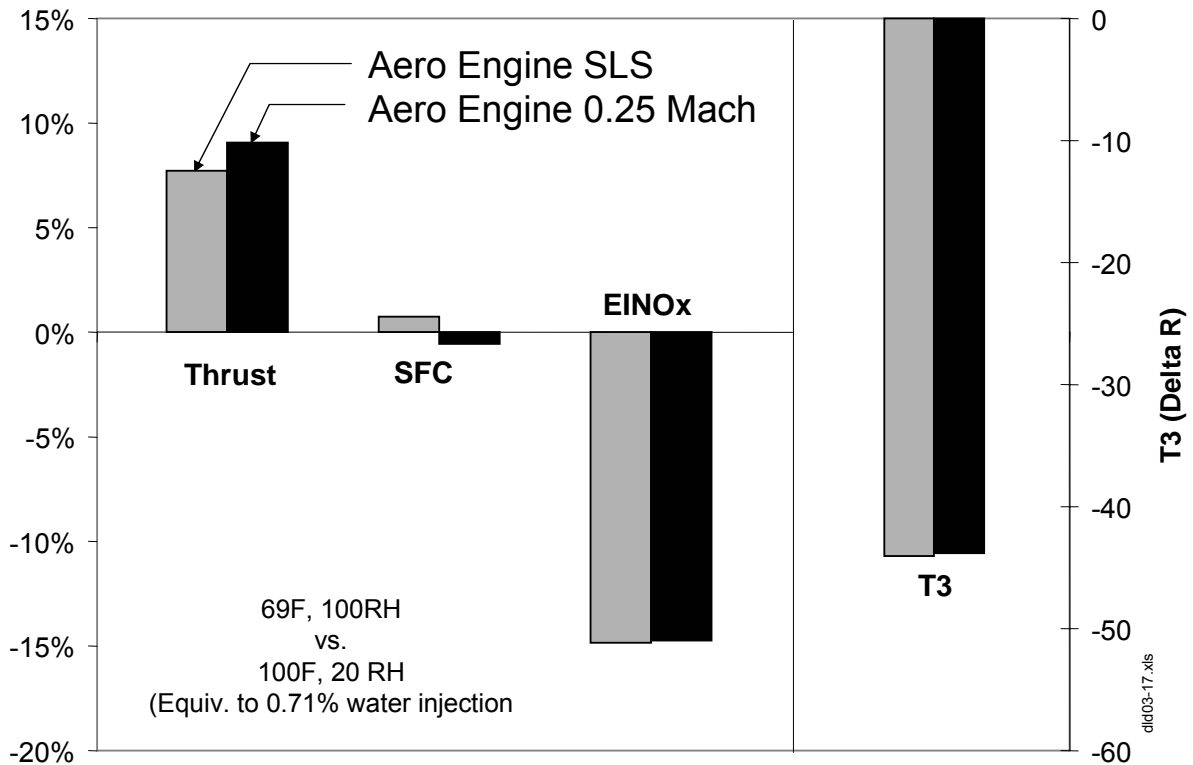


Figure 4.3. Evaporating water in inlet increases thrust, reduces NOx and T3 with little impact on SFC

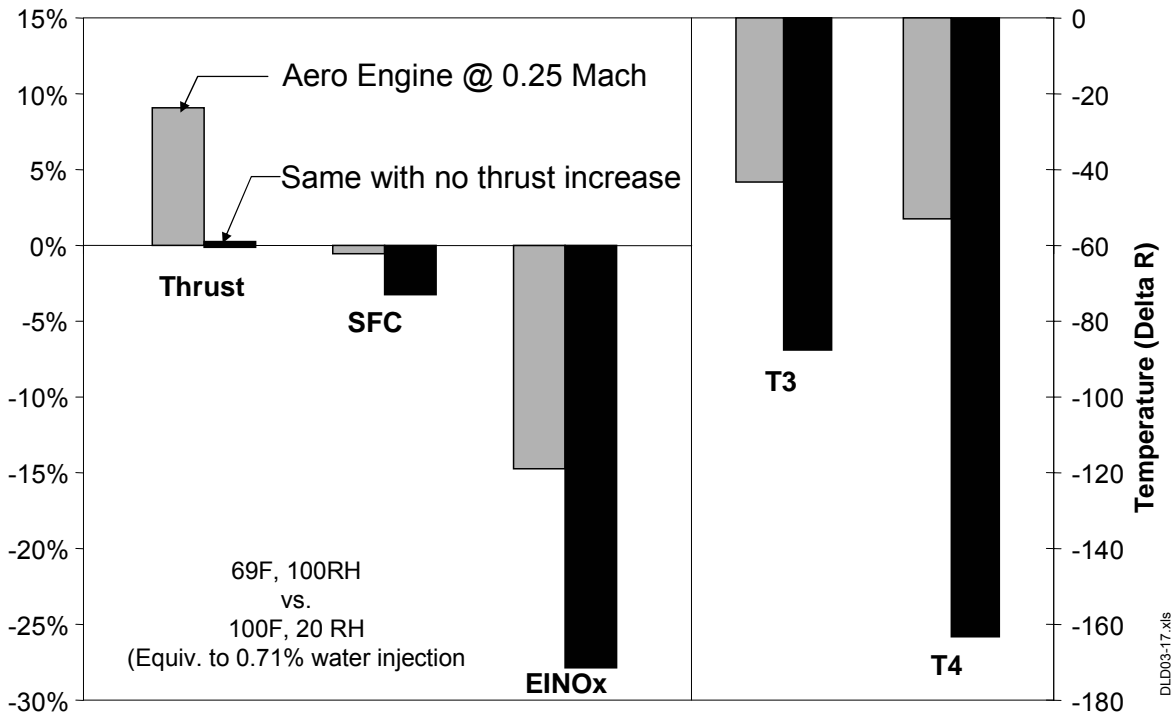


Figure 4.4. Retarding the throttle to keep constant thrust while using LPC water injection further reduces SFC, NOx, T3 and T4

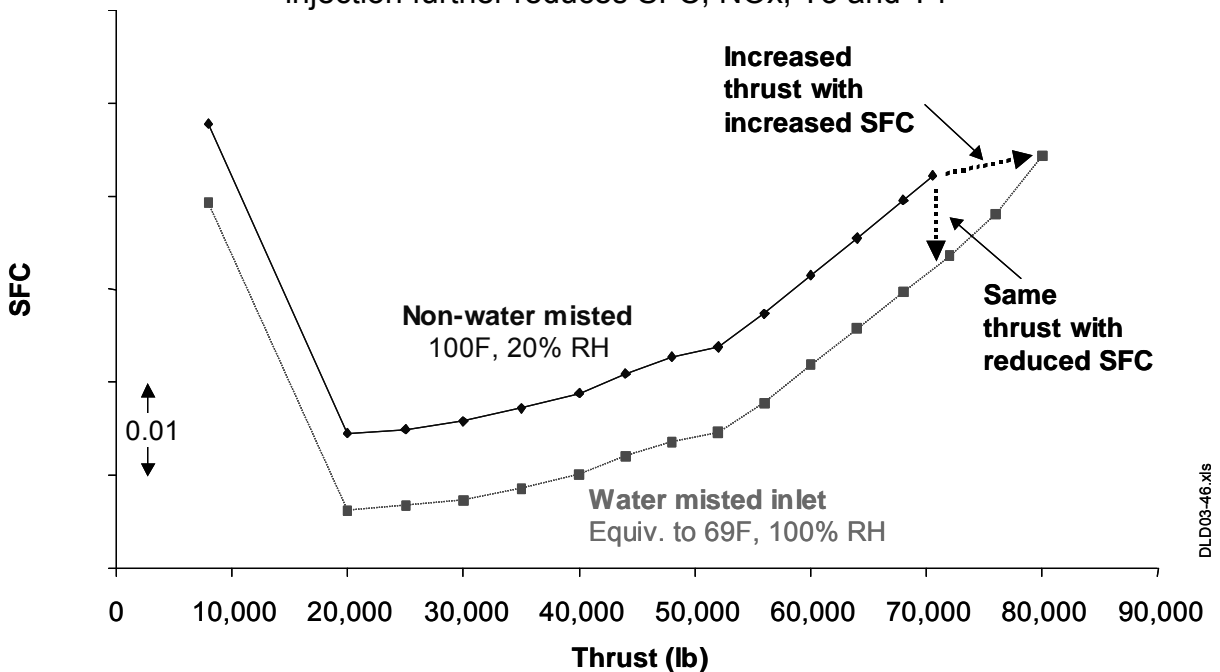


Figure 4.5. Water misting during takeoff either reduces SFC, or increases thrust

From the previous two charts, it appears that by using water misting in the engine inlet, a thrust increase may be gained or SFC can be improved by moving to a new operating line. Figure 4.5 illustrates this relationship.

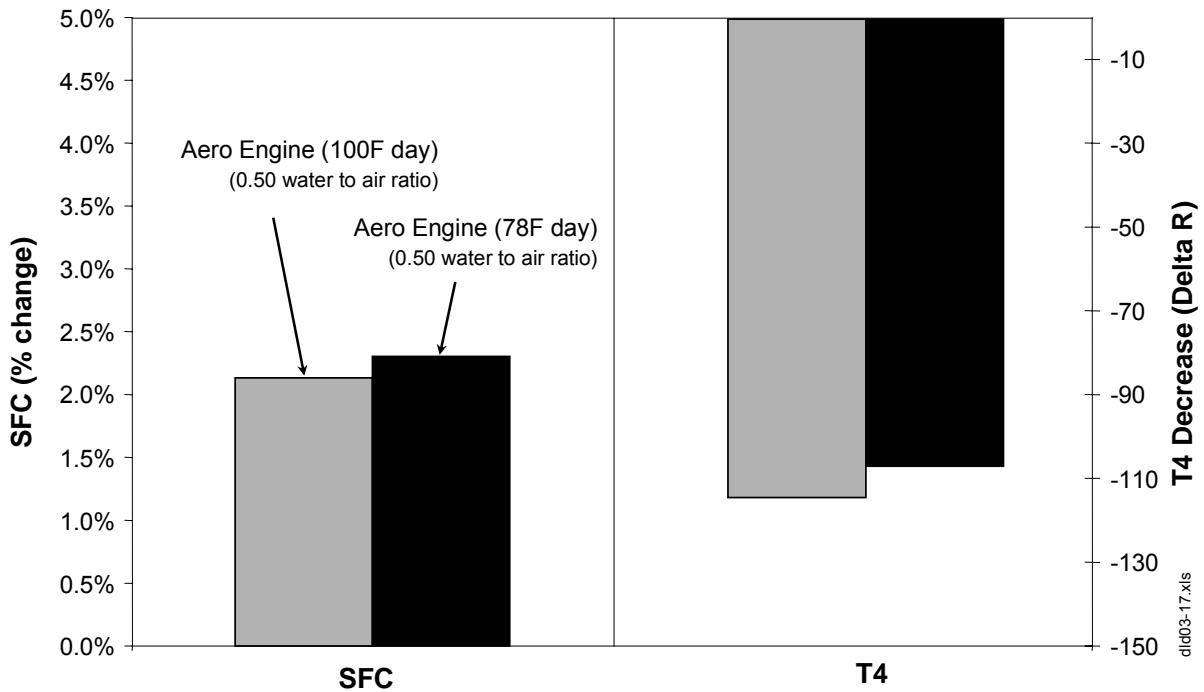


Figure 4.6. Starting temperature doesn't make much difference on SFC or T4 reduction as long as injected water can completely evaporate

Figure 4.6 shows a lesser water injection rate of 50% water to air ratio from two starting temperatures, 100F and 78F. It illustrates that there is not a strong dependency on the starting temperature for SFC and T4 improvements. Thus, as long as the water can be completely evaporated to reduce the air temperature in the inlet and the air saturation point remains less than 100%, engine performance improvements can be had.

For the following LPC, HPC and combustor injections methods, the NASA engine performance program was used to estimate the affect of water injection on the engine. Water is only injected into the engine core in these scenarios.

4.2.2 LP Compressor Injection

Current industrial engines use a Low Pressure Compressor (LPC) water misting injection rate of approximately 0.5% to 0.87% water to core air flow ratio on 90F days. This resulted in a small NOx improvement. To increase the NOx reduction level, the water flow rate should be increased. When the rate is increased to 2.2%, the NOx reduction potential is estimated to be about 50%.⁴⁴ This injection rate should be achievable and may be able to reach levels as high as 3%.⁴⁵

Figure 4.7 compares the data points discussed in section 4.1 from the industrial engine and section 4.2.1 from the aero engine to that of injecting water directly into the LPC and increasing the water flow rate to 2.2%. It shows that when keeping thrust constant, a 3.51% decrease in SFC will be obtained, a 46.5% NOx reduction and large 436R temperature reduction in T4 will be experienced over a non-water misted engine.

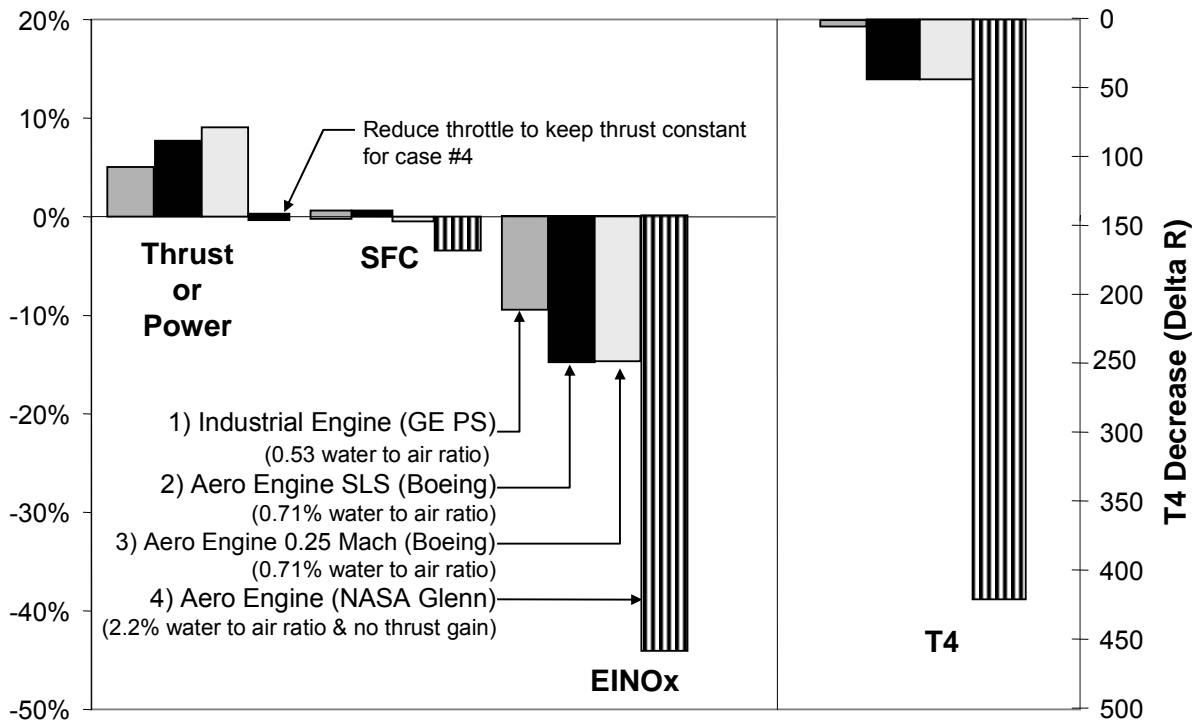


Figure 4.7. Increasing water/air ratio to 2.2% further reduces NOx, T4 and SFC

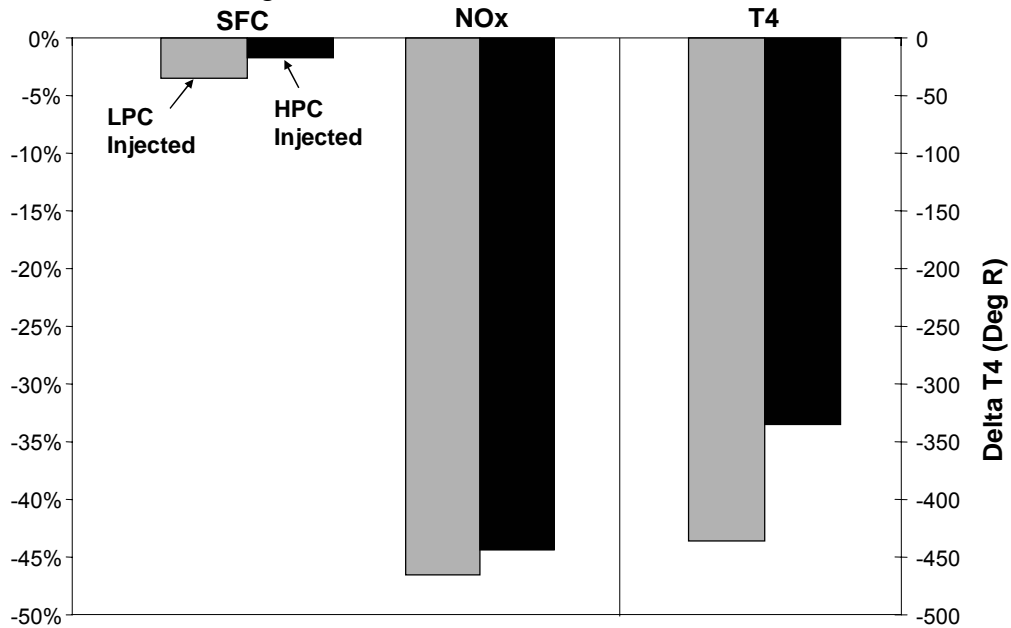


Figure 4.8. HPC injection offers less SFC, NOx and T4 benefit than LPC injection

4.2.3 HP Compressor Injection

Injection of atomized water after the LPC and before the HPC, results in less of a performance improvement than before the LPC. As shown in Figure 4.8, SFC only improves 1.72% for HPC injection instead of 3.51% for the LPC case, NOx decreases 44% instead of 47% and T4 decreases 335 instead of 436 deg R.

4.2.4 Combined LP and HP compressor injection

In the event of freezing conditions, it may be preferable to inject water directly into the HPC instead of the LPC to avoid freezing of the water. However, as the LPC injection method shows a better SFC performance benefit than the HPC injection method, it would be preferable to normally inject water into the LPC.

4.2.5 Combustor Injection

Traditional combustor water injection systems have the advantage that, for a given NO_x reduction, they require much less water to be injected than a LPC or HPC injected system. This is shown in Figure 4.9.

One of the disadvantages of a combustor injected system is the thermal efficiency loss of the engine. In this system, the injected water partially quenches the combustor flame temperature which leads to a reduction in pressure and eventual thermodynamic efficiency. This system also loses the advantage of improving compressor mass flow to offset the thermal loss as in the LPC system. Figure 4.10 shows the relationship that as water injection rate into the combustor is increased, NO_x and thermal efficiency are both reduced, but power can be increased by increasing the fuel flow rate.

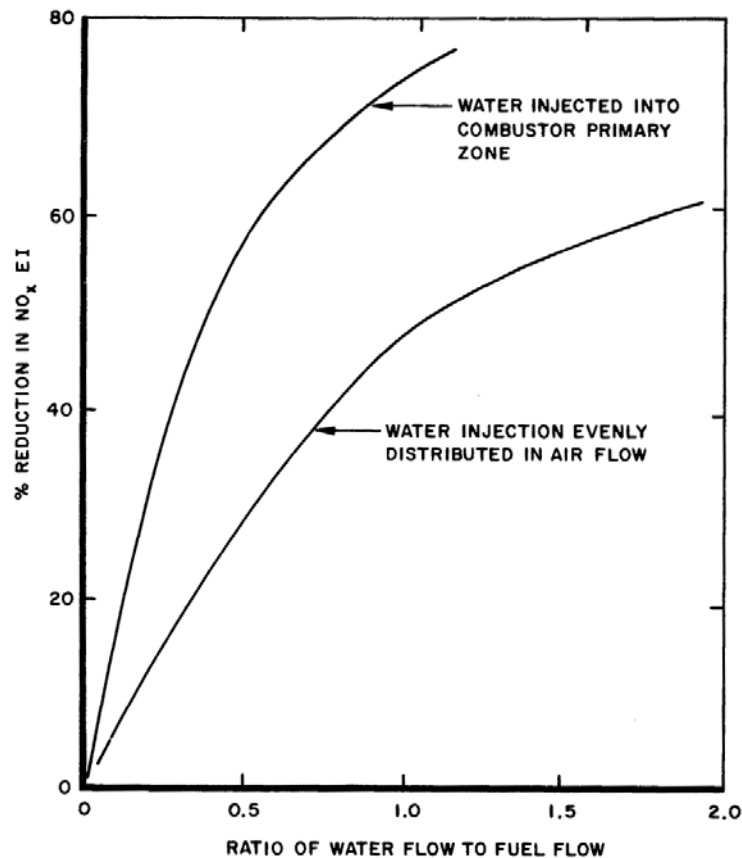


Figure 4.9. Combustor water injection requires less water than LPC injection¹¹

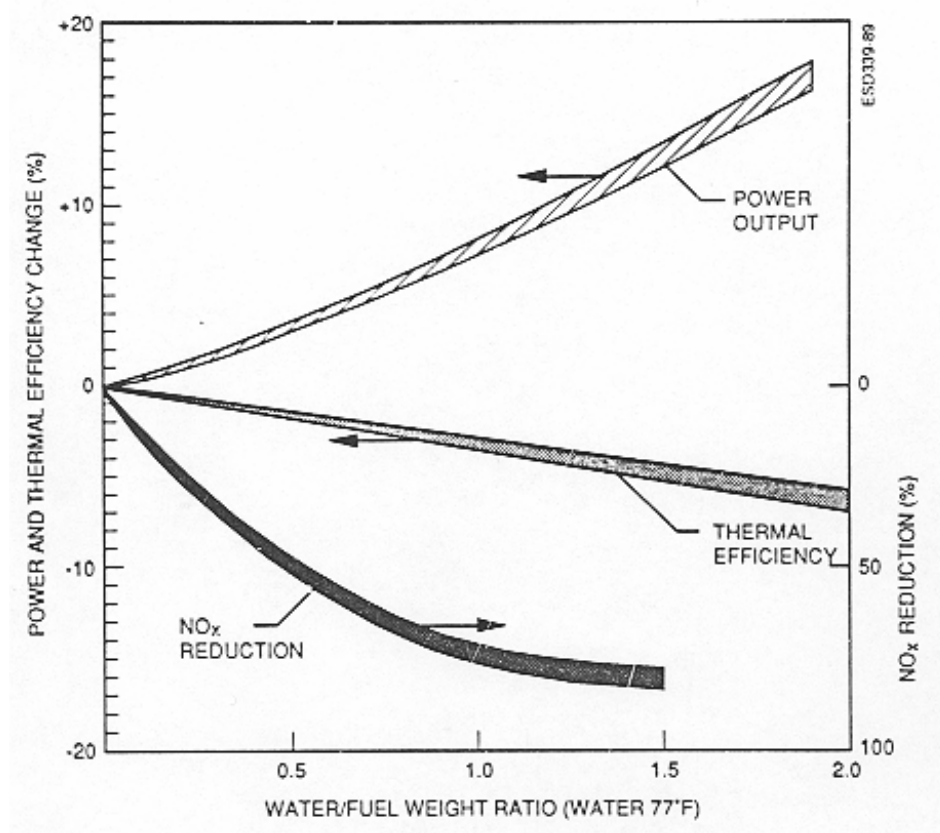


Figure 4.10. Thermal efficiency and NO_x decreases as water injection rate increases⁴⁶

Figure 4.11 shows these relationships as modeled in the NASA engine performance program. For a water to fuel ratio of 0.5:1 on a standard day while keeping power constant, the combustor water injected engine will experience an adverse 2.02% increase in SFC. The engine will achieve a 50% NO_x reduction, a 81R T4 decrease and unchanged T3. This is because only the turbine sees the cooling effect of the water injection.

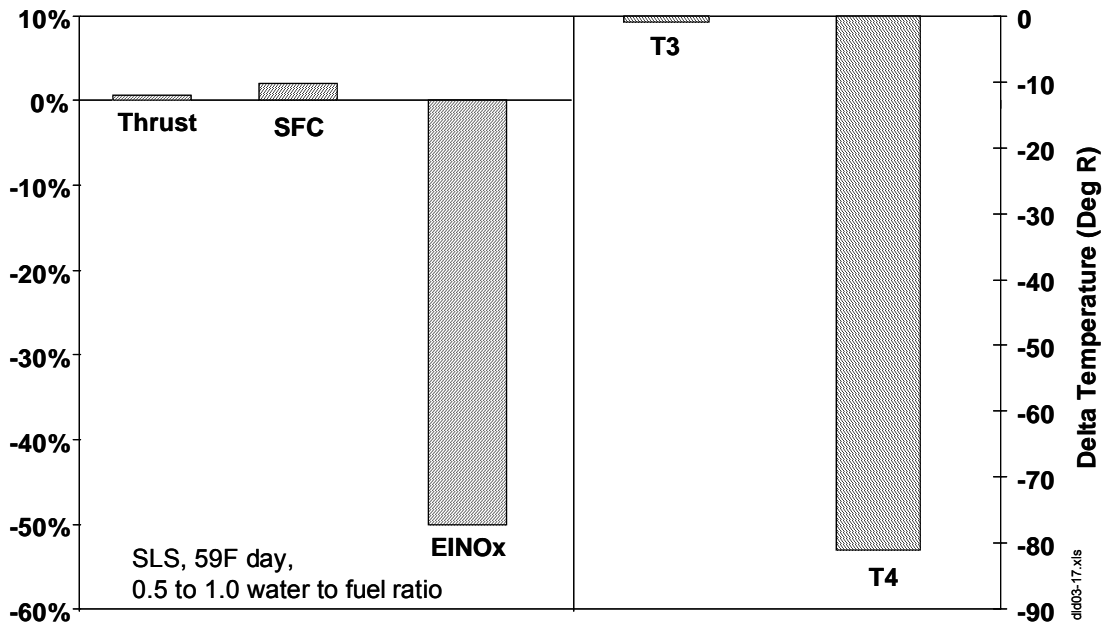


Figure 4.11. Injecting water into the combustor increases SFC while decreasing NOx and T4

4.2.6 System Comparison

Table 4.1 shows the engine summary data for the Baseline engine, LPC, HPC and combustor injection systems using the NASA NEPP. From a fuel efficiency perspective, the LPC injection system is the preferred option.

Table 4.1, NASA NPSS engine performance summary

	ALT	Amb. Temp	MACH	Thrust (lb)	T3 (deg R)	T4	P3 (psia)	SFC	EINOx
Baseline	0	529	0.25	74445	1636.5	3285	621.8	0.3794	58.78
LPC injection	0	529	0.25	74445	1410.2	2849	655.0	0.3661	31.43
HPC injection	0	529	0.25	74445	1427.9	2950	636.3	0.3729	32.69
Combustor inj.	0	529	0.25	74445	1635.6	3204	622.4	0.3870	-

4.3 Airframe System Description

Section 4.2 showed that the combustor injected system was nearly twice as effective in reducing NOx and so required about half the water. Thus, two airframe systems were designed ... one for the combustor injection and one for the compressor injection system.

4.3.1 Airframe system for combustor Injection

For a water to fuel ratio of 0.5:1 to achieve roughly a 50% reduction in NOx and using standard times in mode for takeoff/climbout (section 2.2.3) and fuel consumption rates for a large engine (section 4.4.5), a calculated water consumption rate provides for a water tank capacity of 135 gallons for takeoff and climbout conditions. Figure 4.12 shows the airframe system layout.

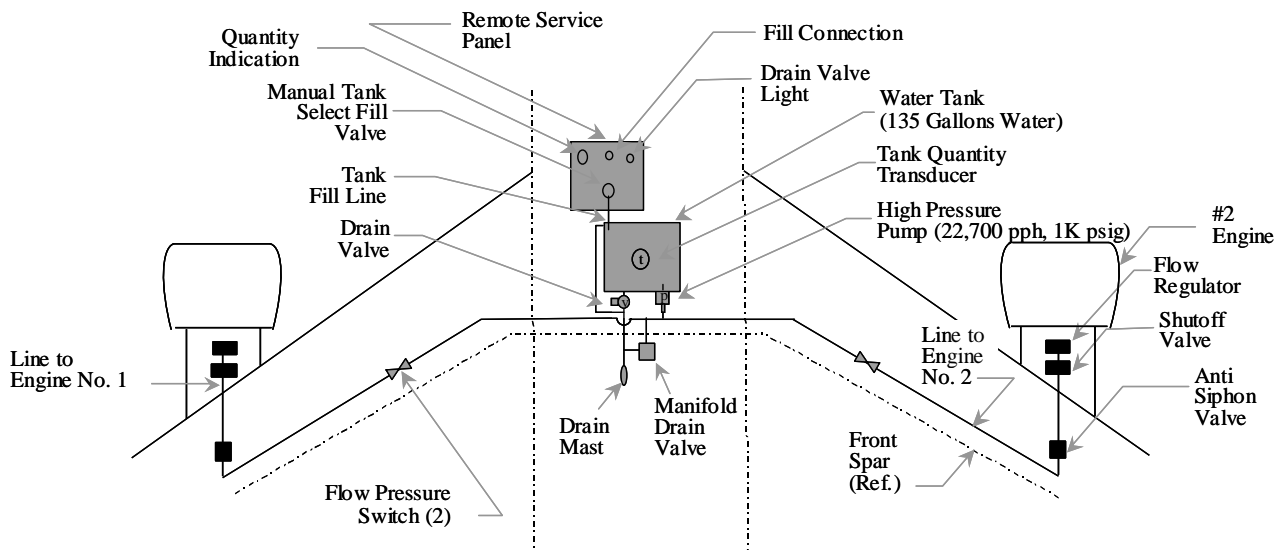


Figure 4.12. Airframe water system for direct combustion injection system

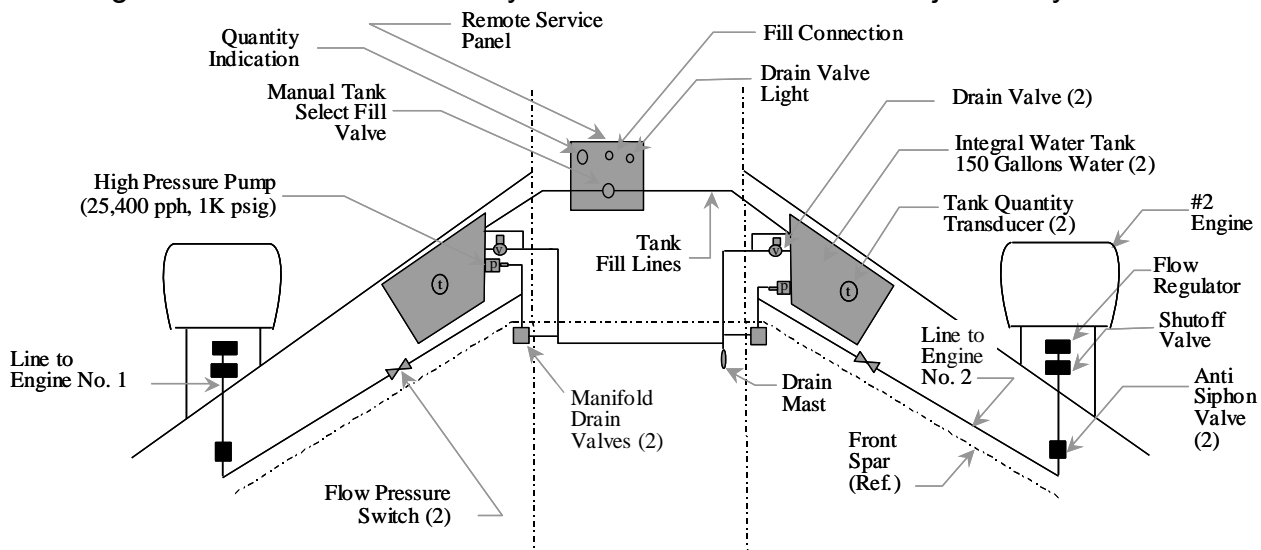


Figure 4.13. Airframe water system for LP compressor injection

The advantage of this system is that it uses one high pressure pump and has only one drain mast. The disadvantage is that it requires a single, centrally mounted water tank.

4.3.2 Airframe system for LP compressor injection

For the LP compressor injected system, more water is required to achieve the same NOx reduction as the combustor system. Using the assumed 2.2% water to core air flow ratio, and the standard time in mode of section 2.2.3, a water tank capacity of 300 gallons was estimated. It uses two high pressure (534-750 psig) pumps each capable of a 26,000 PPH flow rate. Figure 4.13 shows the layout of such a system.

The system uses two water tanks, each located in the forward part of the wing as shown in Figure 4.14. For safety reasons, there are areas in the wing near the

engines that do not contain fuel. In the event of a catastrophic engine failure (e.g. rotor burst), the areas around the engine where debris might penetrate the structure or wing are kept free of fuel. These areas are called “dry bays” and are ideally suited to house the water tanks as shown below.

The dry bay available area in each wing is capable of holding 407 gallons of water. However, each water tank will be designed to hold 150 gallons of water that will be sufficient to supply the engine with water to at least 3,000 feet altitude. In both designs (4.3.1 and 4.3.2), there is a centrally located water fill and control panel that is ground accessible.

The water tanks should be filled each time the airplane lands and not carry water to the destination as the water would freeze in flight inside the tanks. In older systems, the water lines and water dump mast were heated so that water could be jettisoned in the event the water was not used during takeoff and also to drain the lines of any remaining water.

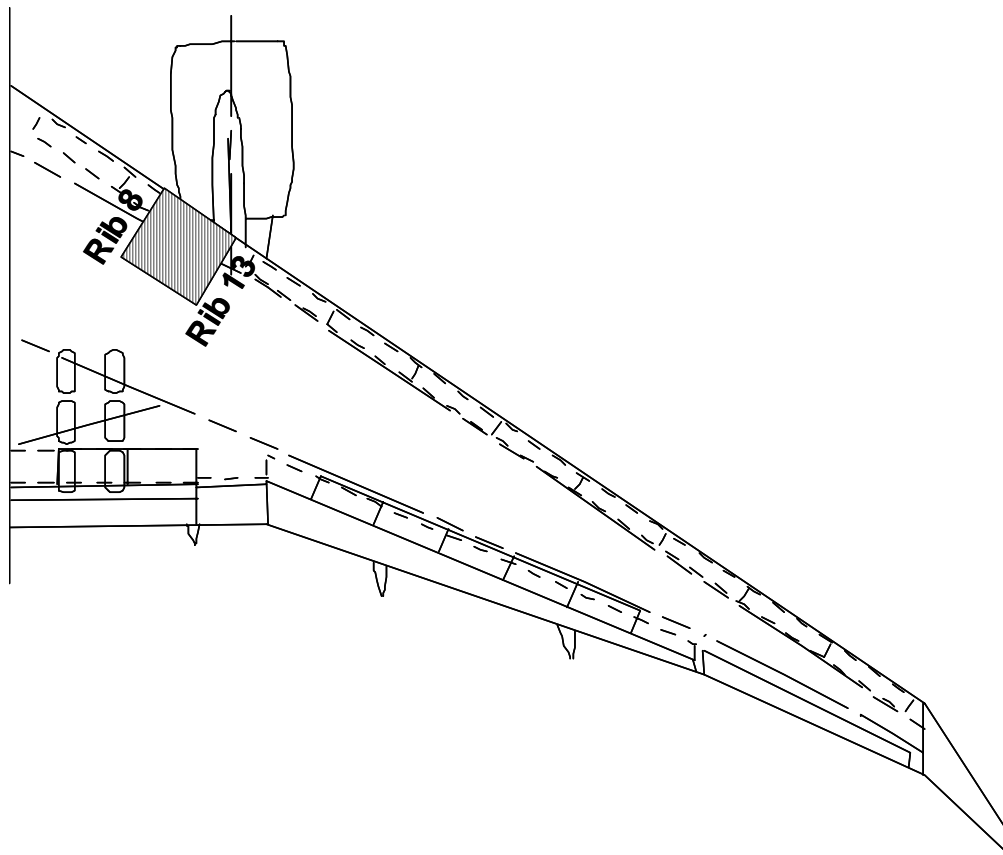


Figure 4.14. 150 gallon tank located in each wing dry bay

4.4 System Performance Summary

4.4.1 Weights

4.4.1.1 Airframe and Engine – The weight of the water misting system and combustor injection systems for the airframe and engine are estimated to be no greater than 360 lbs. This was determined from the weight of a 747-200 water injection system. Weight improvements could be made over the 747 system. Areas of improvement are:

- 1) Water bladders in the composite wing could possibly be replaced with a sealant type coating that would be applied to the inside of the integral water tanks within the wing.
- 2) The 36 KVA electric motors could possibly be down-sized. The combustor injection system needs less water flow. For the LPC system the motor and pump for the 747 provides the same required water flow rate. However, if HP compressor bleed air could be used to assist in the atomization of the water at the engine injection point, lessening the required pressure (534-750 psig) from the water pumps, then the power required for the pumps could be lessened which would lead to lighter pumps.
- 3) Improved technology. The 747 water injection system was designed over 30 years ago. Weight improvements in components may have been achieved during that time.

4.4.1.2 Water weight – The water weight for the combustor injection system is 1,127 lbs. The water weight of the LPC injection system is 2,505 lbs. (300 gallons at 8.35 lb/gal). 30% of the LPC system water weight is consumed during the takeoff roll and the rest consumed during the initial climb out period.

4.4.2 Thrust

Engine thrust is primarily a function of the mass and acceleration of the gasses exiting the fan and engine core nozzles. This is the familiar thrust equation $\text{Thrust (F)} = \text{mass (m)} \times \text{acceleration (a)}$. By adding water to the engine, the mass flow is increased and so thrust increases.

For this study, it is assumed that the additional available thrust from water injection will not be used. This avoids any safety related issues if there was a failure with the system. Although water injection would enable a smaller, lighter weight engine to be used (this would improve fuel efficiency), the initial cruise altitude capability of the aircraft could be sacrificed. The engine size is determined by the takeoff and cruise altitude capability.

4.4.3 Takeoff, Climb and Range Performance

During takeoff and climbout, because SFC is affected by the type of injection system used, the combustor injected system will use 51 lbs. more fuel while the LPC system will use 90 lbs. less fuel.

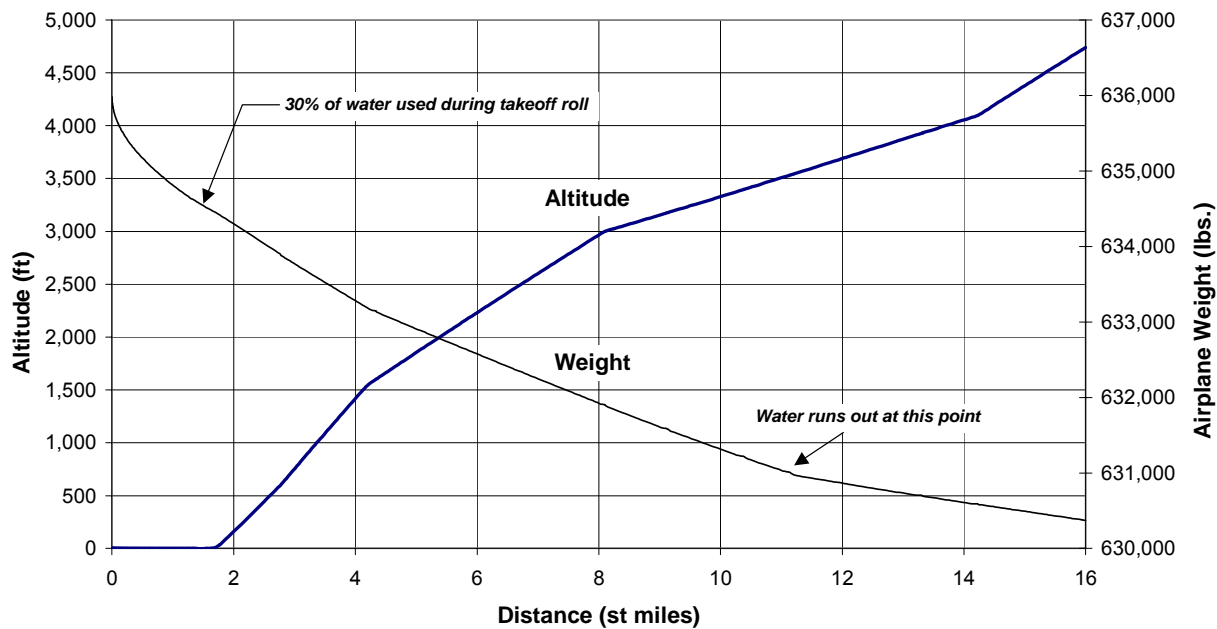


Figure 4.15. 30% of water (750 lb. for LPC system) is used during takeoff roll, so climb performance is minimally affected by weight

Both systems will use approximately 30% of the water during the takeoff roll. All of the water will be consumed by the time the aircraft reaches 3,560 feet. Figure 4.15 shows the how the weight of the aircraft decreases throughout the climb sequence by using both water and fuel.

For aircraft that are range limited by the amount of fuel that can be carried, there is a slight range penalty of 7 nmi. for carrying the water injection systems. For aircraft that are limited by the take off gross weight of the aircraft, carrying the water injection system and the 2,505 lb. of water will replace that same amount (weight) of jet fuel. Thus, the aircraft range is reduced by 80 nmi.

A positive variable for the system is the reduction in T4 when using water injection. Figure 4.16 shows that the highest turbine inlet temperature occurs during the takeoff roll and up to the point right after takeoff where the throttles are reduced (cutback). When using LPC water injection, Section 4.2.2 showed a 436 R decrease in T4. This reduction in T4 is shown in Figure 4.16 by the dashed line. Thus, peak temperatures that the engine will experience with water injection would now be at the top of climb and the very highest it will ever see are reduced by more than 200 R from the previous takeoff peak value. This would no doubt improve the life of the current engine turbine inlet nozzle guide vanes and HP turbine blades.

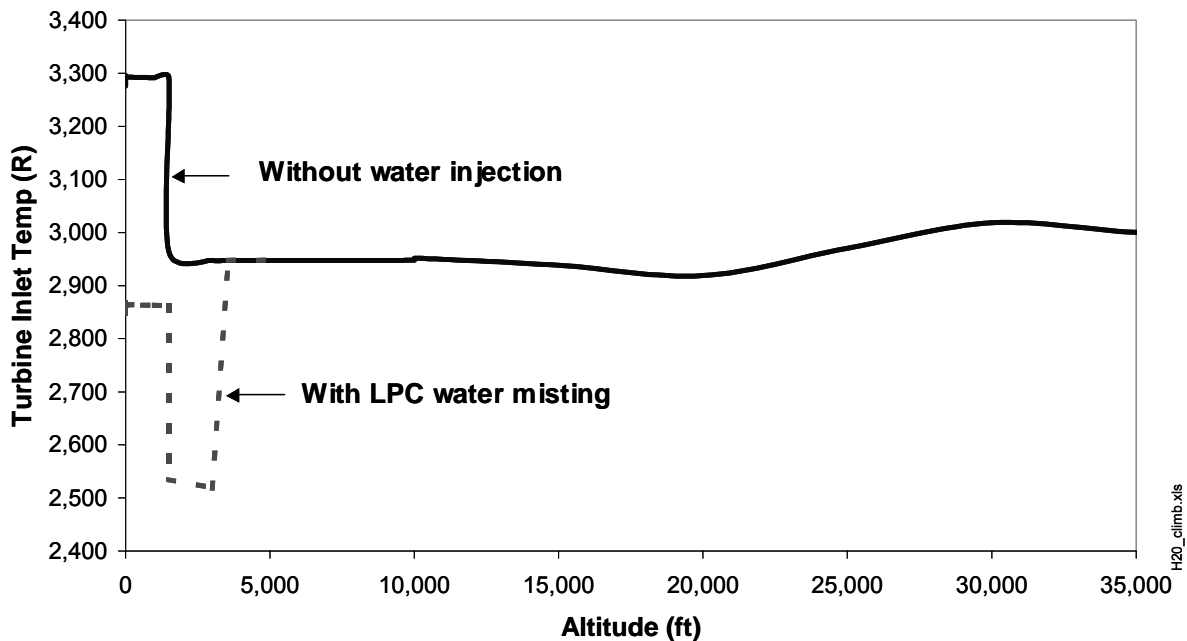


Figure 4.16. Water misting greatly reduces T4 during the most critical phase of flight on current technology engines.

However, as future aircraft engines increase their fan by pass ratios, this may lead to decreases in T4 levels at takeoff and increased levels at top of climb. Thus, the temperature reduction benefit might not be as great for future engines than for current technology engines.

4.4.4 Fuel Use

Very little fuel use impact will be experienced by the aircraft, either during the takeoff, climbout, or the cruise parts of the flight. However, the following documents these small changes.

For the combustor water injected engine, a 2% thermal efficiency loss is experienced during takeoff. This results in a 51 pound (7.6 gallon) fuel use penalty. For the LPC injected system, a 3.51% SFC improvement is anticipated under standard day (non-freezing) conditions. This results in a 90 pound (13.4 gallon) fuel savings. Figure 4.17 shows the changes in fuel use for the baseline engine as well as the engines with combustor and LPC injection methods.

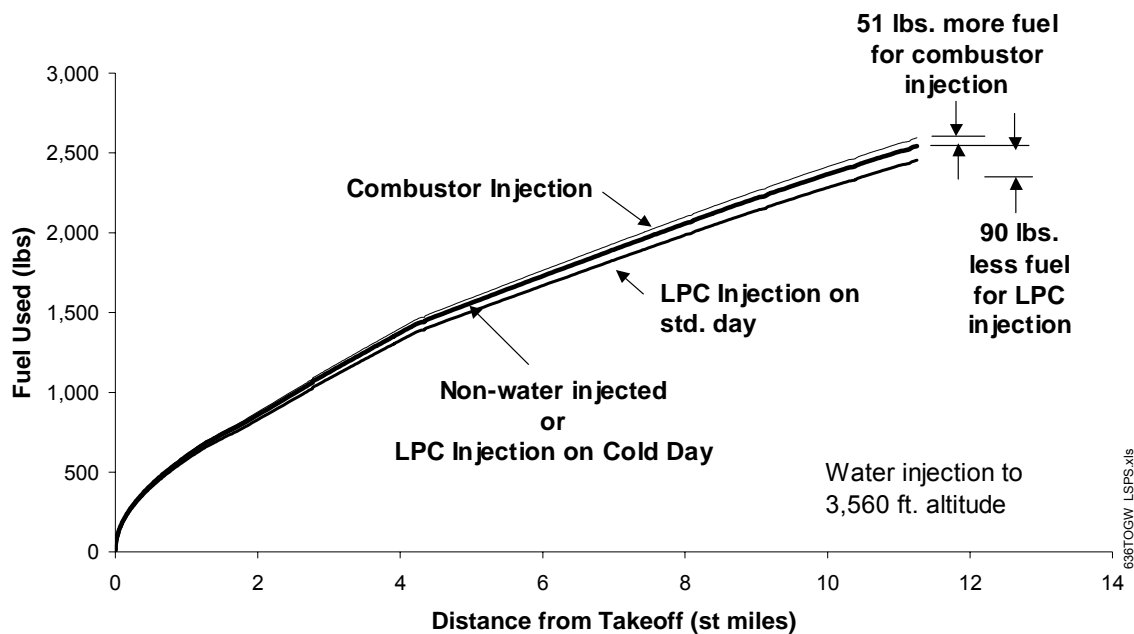


Figure 4.17. Combustor water injection uses 51 lb. more fuel from takeoff to 3,560' altitude while LPC injection uses 90 lb. less fuel than base engine on standard day

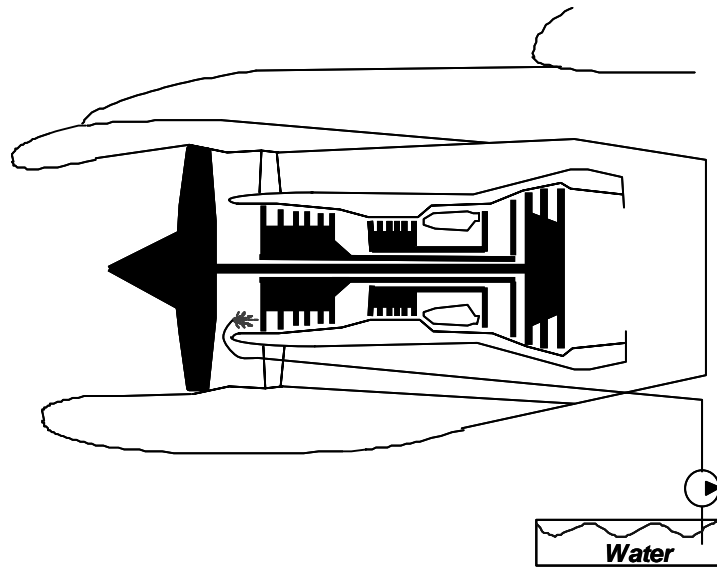


Figure 4.18. Water wash is used to clean engine and restore performance

During cruise, any weight increase of the airplane will require additional fuel. However, as this system is only expected to weigh less than 360 lbs, a very small fuel use penalty will be experienced. For the study airplane on a 3,000 nmi mission, a 63 lb (9.3 gallon) fuel use penalty can be expected.

When using water misting injection into the LPC for takeoff, some cleaning of the compressor may occur.⁴⁷ Presently some aircraft operators use engine water washing during maintenance periods to clean the compressor and turbine sections of the engine to restore engine performance (Figure 4.18).

The amount of performance improvement from water wash is not well documented.

On 747 aircraft, average performance deterioration, from 3 engine manufacturers, reaches the 3-4% level after several years (Figure 4.19). This deterioration is not only from dirty compressor and turbine blades, but mechanical deterioration as well. When water washing an engine, it is generally believed to contribute a 0.5 – 1.0% SFC restoration. If this level of restoration were achieved, it would result in a 294,263 to 588,525 lb. fuel savings per airplane per year. However, as this benefit is speculative with using water misting injection, it will not be included in the study.

4.4.5 Emissions

NOx Emissions levels are typically referenced to Emissions Indices or EINOx. This is the emissions level (grams) divided by the fuel use (kg). Standard ICAO emissions databases list the EINOx and fuel use numbers for takeoff, climbout, approach and idle conditions. Figure 4.20 shows an example of such a data sheet.⁴⁸ For this exercise, ICAO NOx emissions for a GE90-85B engine (ID 2GE064) was obtained and used to validate the NASA NEPP emissions data. As the NEPP data is intended to simulate a generic GE90 or PW4000 engine, the emissions reduction potential is similar to either engine. Appendix A shows more on the calculation methodology and matching of results to Boeing predicted and actual engine data points.

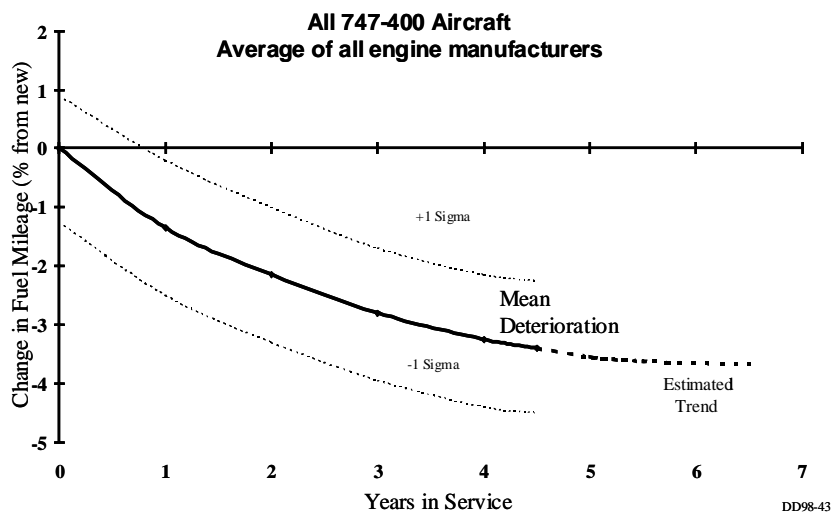


Figure 4.19. Deterioration can reduce SFC

Mode	Power Setting (%Foo)	Time (mins)	Fuel Flow (kg/s)	Emissions Indices (g/kg)			Smoke Number
				HC	CO	NOx	
Take-Off	100	0.7	3.169	0.04	0.15	47.28	
Climb Out	85	2.2	2.583	0.04	0.16	35.7	
Approach	30	4.0	0.852	0.07	1.1	16.73	
Idle	7	26.0	0.292	0.45	13.67	5.69	
Number of Tests				5	5	5	5
Number of Engines				3	3	3	3
Dp/Foo (Average) (g/kN) Or SN (Max)				0.6	16.51	61.92	0.5
Dp/Foo (g/kN) or SN (Sigma)							
Dp/Foo (g/kN) Or SN Range				0.3 - 0.92	14.4 - 18.4	57.9 - 65.3	0 - 1.92

Figure 4.20. ICAO emissions data from the GE90-85 engine (2GE064) was used to validate the NASA NEPP emissions results⁵⁰

4.4.5.1 Taxi Emissions – The amount of time the aircraft is taxiing, and the emissions index, both have a large affect on the total amount of emissions generated. Although the engine is operating for a long period of time during taxi (26 minutes), it has a very low NOx emissions index (grams of NOx per kg of fuel burned) and therefore contributes a small amount of NOx during the LTO cycle. Using the GE90-85B emissions database above, the idle portion contributes only 0.64% of the cycle NOx. Conversely, CO and HC emissions have high levels at this low power setting, contributing 34% and 35% of the LTO CO and HC emissions. Other engines typically have even high contribution percentages of CO and HC at idle conditions. Figure 4.21 shows the relative emissions contributions for the various phases of the LTO cycle. Thus, using water injection during the taxi phase of the LTO would have little impact on NOx, but increase CO emissions. For this reason water injection was only considered for takeoff and climb-out conditions.

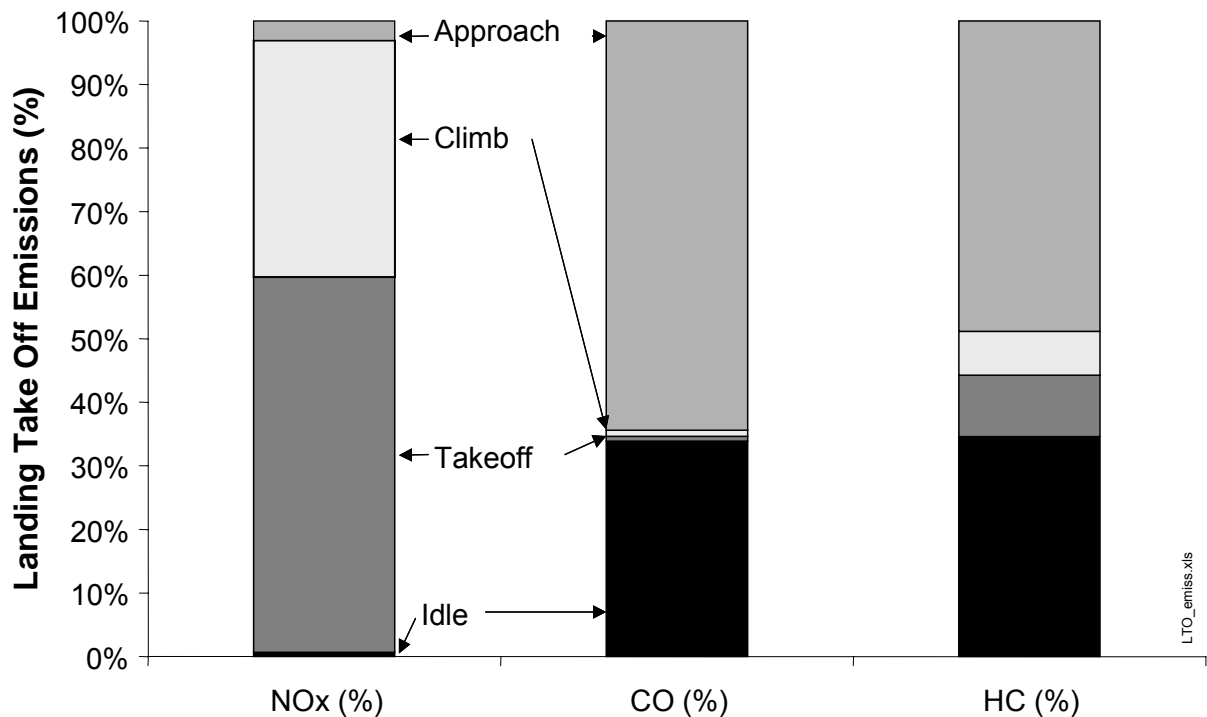


Figure 4.21. As little NOx emissions are generated during taxi, water injection was not used for this phase

4.4.5.2 Takeoff Emissions – The takeoff and climbout portions of the LTO cycle contribute the most to an airplane’s NOx emissions. As NOx is the emissions of focus at airports, water injection would be able to help achieve reductions in local airport emissions by using it from the moment takeoff power is commanded to the point of water exhaustion which occurs outside of the airport boundary.

The governing mechanism in water injection is the lowering of the stoichiometric flame temperature.⁴⁹ This tends to be strictly a thermal phenomenon and typically lowers prompt NOx a very small amount, which is a small contributor to overall NOx production.

The primary zone stoichiometry has an effect on the effectiveness of water in reducing emissions.⁵⁰ Fuel-rich primary zones being more susceptible to improvements in NOx reduction with water injection.

Using the NASA NEPP results and Boeing airplane performance decks for validation, Figure 4.22 shows the altitude versus distance profile for the study airplane. In addition, it also shows the standard NOx generation profile and the reduced LPC water misted NOx generation. At 3,560 feet, the 300 gallons of water will have been exhausted. At this point, the amount of NOx reduction will have been 49.2 lb of NOx, achieving a 46.5% reduction in takeoff and climbout NOx.

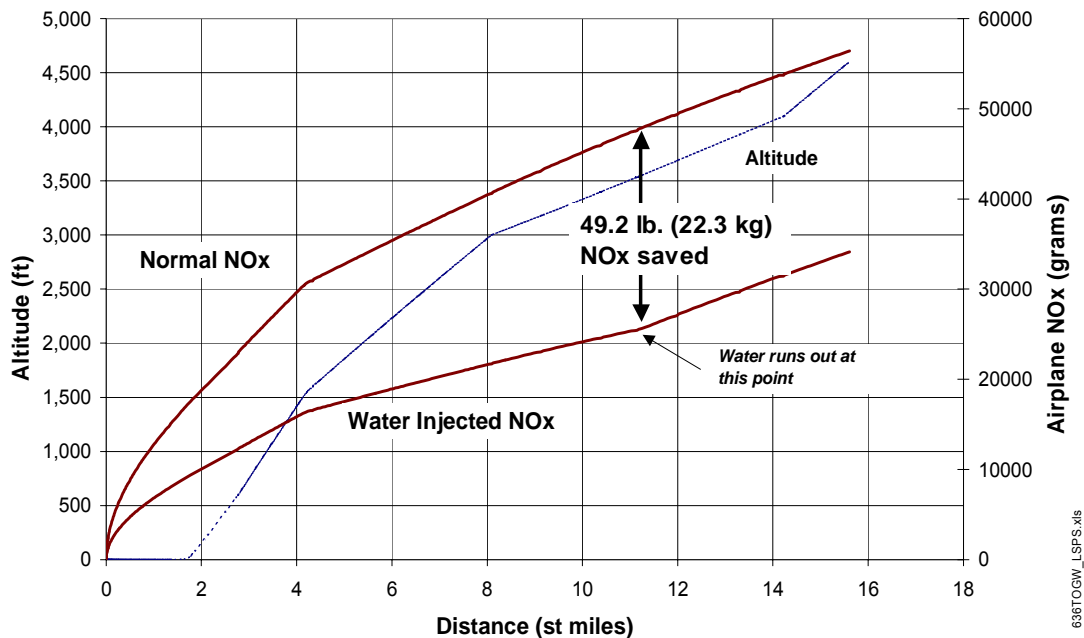


Figure 4.22. NOx is reduced 46.5% during takeoff and climb-out saving 49 lbs. of NOx emissions to 3,560 feet (beyond normal LTO cycle altitude)

The NOx emissions reduction during this specific takeoff procedure, and airplane configuration, is more than what would be achieved when simply calculating a 46.5% NOx reduction when using the ICAO LTO cycle for takeoff. The 49 lbs. NOx reduction occurred when using 300 gallons of water, which took the airplane to an altitude of 3,560 ft and water misting time interval of 3.3 minutes versus the typical 3,000 ft and 2.9 minutes for the LTO cycle. In addition, fuel savings are realized in our calculations which further reduces total NOx emissions.

Everyday NOx savings for aircraft in use would most likely be lower since they typically operate in the 70% load factor range instead of the study's 100% load factor and 100% engine thrust.

The amount of NOx savings is also dependant on the type of engine used. Smaller, lower pressure ratio engines would have less reduction potential while larger, higher pressure ratio engines would achieve more. For example, the GE90-85B engine, which closely resembles the study engine, has a total LTO NOx emissions rate of 108 lbs. per LTO cycle. The smallest 777 engine is the PW4077 that has a NOx emissions rate of 63 lbs per LTO while a larger PW4098 engine has a level of 142 lbs.

The study engine, and 49 lb. NOx reduction calculation, represents an average sized engine for the 777 with a reasonable reduction potential level. Releasing exact reduction levels would involve disclosure of engine company proprietary data.

4.4.5.2 HC and CO Emissions Tradeoffs

Typically, there are tradeoffs required in order to achieve this level of NOx reduction. One of the design philosophies behind low NOx combustors is to well-mix the fuel-air mixture prior to combustion and achieve a more homogenous process that reduces hot burning zones within the combustor. However, as these high temperature zones are reduced by leaning the fuel-air mixture, CO and HC emissions tend to rise as illustrated in Figure 4.23.

Indeed this relationship also exists for the water misting intercooler system. As water is injected to reduce NOx, CO and UHC climb as shown in Figure 4.24.

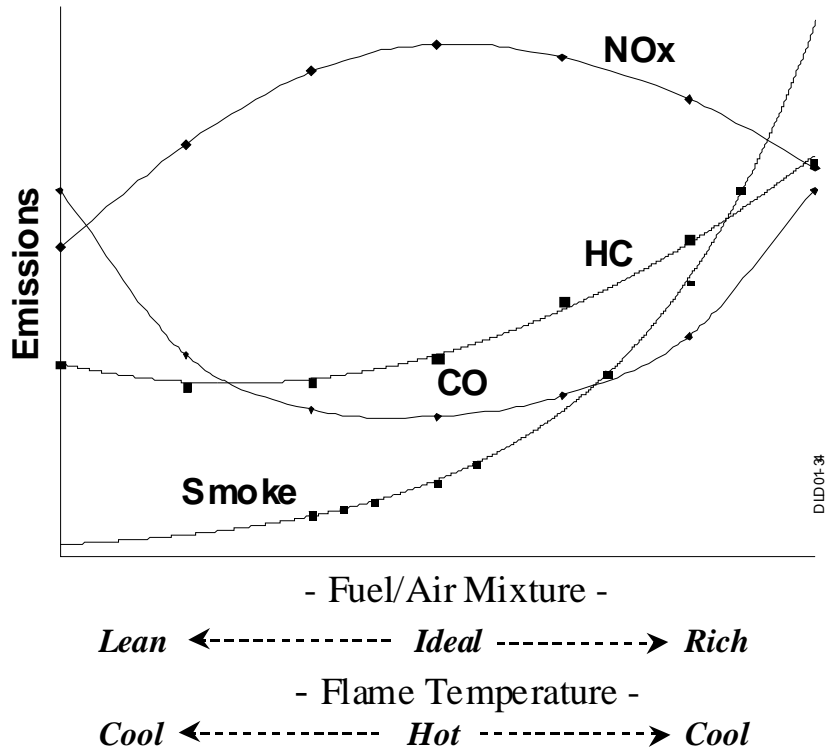


Figure 4.23. Emissions Relationship

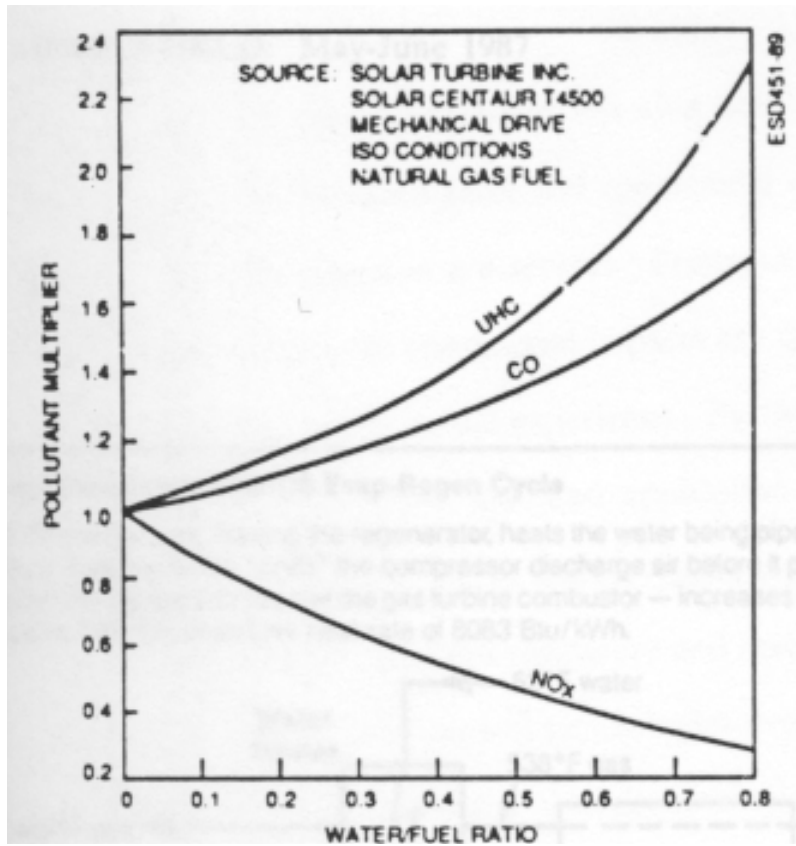


Figure 4.24. HC and CO increase with decreasing NOx⁵⁴

Table 4.2. Aeroderivative engines used in Figure 4.25

Engine Model	LM2500	LM6000
Aero Engine Parent	CF6-6	CF6-80C2
Power (shaft HP)	31,200 to 42,000	56,795 to 58,932
Aero certification date	1970	1985
Combustor	Annular with 30 fuel nozzles	Annular with 30 fuel nozzles
Pressure Ratio	18:1	29:1
NOx (ppmvd, ref. 15% O ₂) on distillate fuel	316	403
NOx (with water injection)	42	42

The rate at which CO and HC emissions climb is dependant on the engine and, no doubt, the engine operating conditions. Figure 4.25 show a difference in the CO production rate between two GE industrial engines, a LM2500 and LM6000, that are further described in Table 4.2.

The LM6000 engine shows practically no increase in CO until a water to fuel ratio of 1.4 is reached. However, the LM2500 engine shows CO increases as soon as water is introduced into the combustor.⁵¹ This difference in behavior may be due to the engine combustor operating characteristics. Namely, the LM2500 engine's relatively low pressure ratio of 18:1 versus the newer LM6000 engine's pressure ratio of 29:1. Thus, the LM6000 engine is operating at a significantly higher combustor pressure and therefore temperature, both of which tend to reduce CO emissions.

As the LPC study engine is operating at an approximate equivalent 0.5 water to fuel ratio, and the combustor operating conditions are more in line with the LM6000 engine, the CO level may remain essentially unchanged. However, this has yet to be proven and it could even increase some 50% if it follows the lower pressure ratio LM2500 engine trend.

Generally, smoke has been reported to reduce when using water injection. Figure 4.26 shows that, for a combustor water injected engine using Jet-A fuel, smoke is reduced as the water rate is increased. No reported results on smoke emissions were found for LPC injected engines.

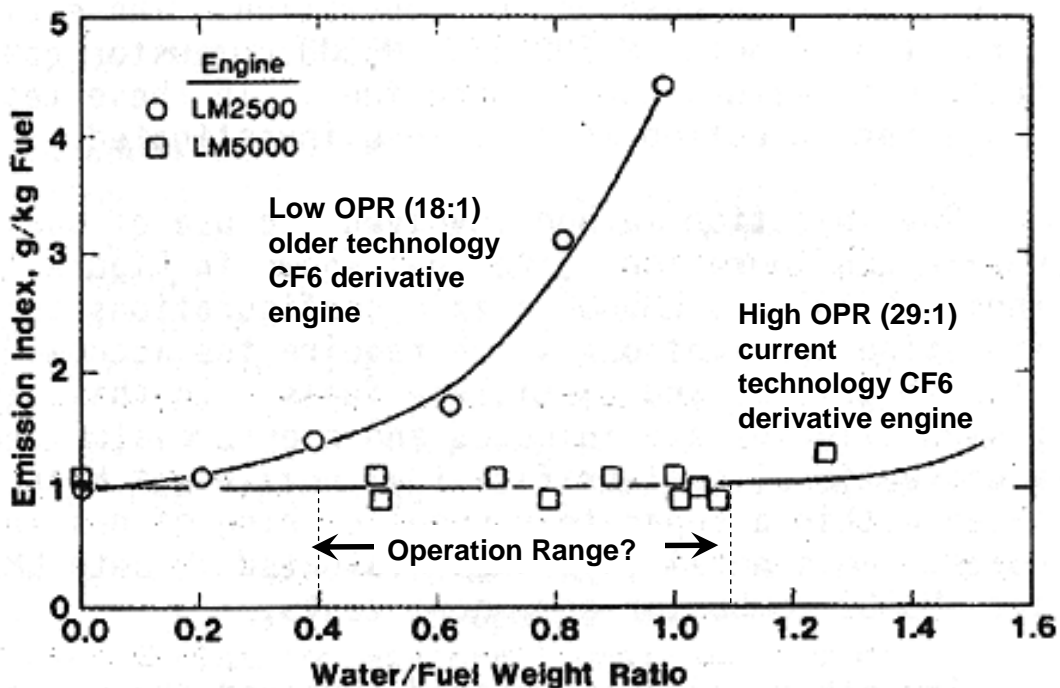


Figure 4.25. CO generation by water injection is dependant on engine type¹⁶

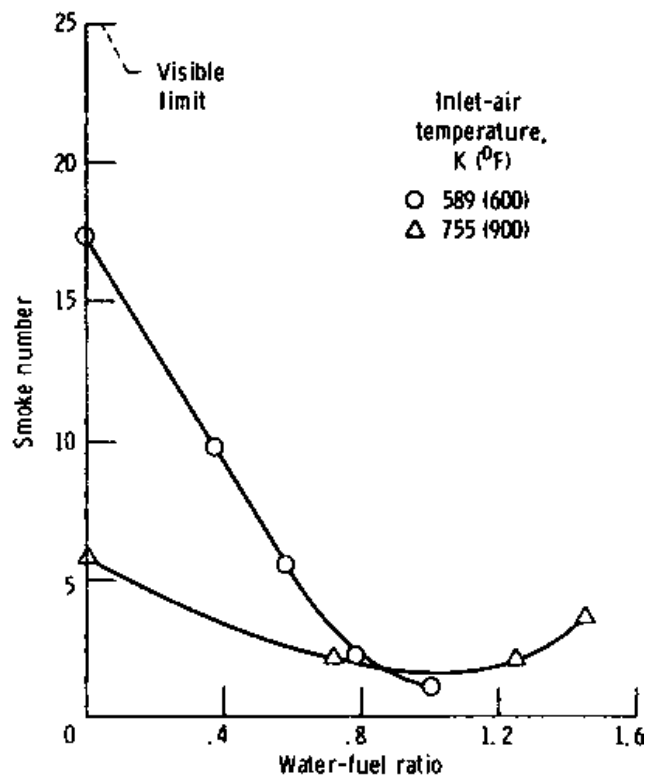


Figure 4.26. Test results show that smoke may decrease with water injection⁴

4.4.6 Noise

When water is added to the core of the engine, the total engine core flow density increases. Since a constant thrust is being maintained in the takeoff cycle, the velocity of the core needs to be reduced to compensate for the increased mass flow. For this particular engine cycle, the fan flow mass and velocity decreased to maintain the same thrust level. The mass flows and velocity of the core and fan flow will determine the noise level of the engine. Figure 4.27 shows that as the engine core mass flow increases with the addition of water, the core velocity is reduced as well as the fan mass flow and velocity. Together, these averaged flows result in a 0.61 db reduction in engine noise. This noise benefit may be lost if the engines were resized to take advantage of the added available thrust.

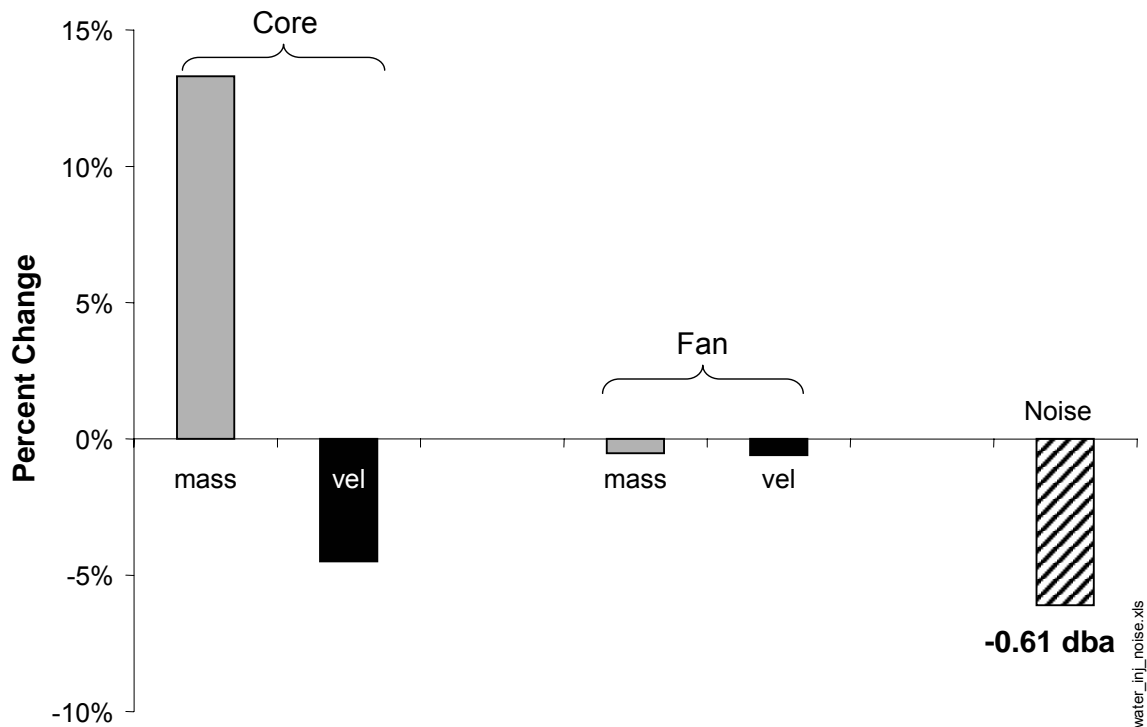


Figure 4.27. Noise decreases slightly because mass averaged jet velocity decreases

4.4.7 Maintenance

Due to the large decreases in turbine inlet temperature documented in Sections 4.2 and 4.4 of this report, it is anticipated that increased hot section life will be achieved in current technology engines when using water misting intercooler technology. This could have a large impact on reduced costs for newer aircraft engines. However, as this cost savings is not easily calculated and data are currently being collected, it is not included in this study.

Historical water injection system and engine maintenance costs for the 747-100 and 747-200 aircraft were reported in section 2.4.1 to be \$20.62 (2003 dollars) per takeoff. As the 777 has two engines as compared to 4 engines for the 747, this cost will be reduced to \$10.31 per takeoff.

Other maintenance concerns and comments from Boeing and engine company reviewers are listed in Appendix C.

4.4.8 Water Conditioning and Cost

According to airport industry agreed upon service costs, demineralized/conditioned water (includes transportation to the aircraft) costs are approximately \$23.59 per airplane service. About half of this cost (\$12.28) is for the tankering of the water to the airplane. This leaves \$11.31 for the conditioned water cost, or \$0.038 per gallon. For production of water at the airport, this water cost would decrease to at least \$0.026 per gallon (Appendix B) or could even go down to as low as roughly \$0.01/gallon (Appendix C) for an optimized system.

The airplane water service cost is derived in the following manner ... airports agree to provide services according to mutual assistance ground service agreements. Table 4.3 shows the average rate per hour for providing conditioned water to the aircraft. A typical 600 gallon ground service vehicle⁵² was assumed to be used for the study. As the study airplane uses 300 gallons of water, the water truck would be able to service two large aircraft per hour ($\$47.12 \div 2$ services = $\$23.59$ per service).

Table 4.3. Water conditioning and delivery costs⁵³

Seattle	\$43.54
Anchorage	\$50.07
<u>Honolulu</u>	<u>\$47.89</u>
Average	\$47.12 per hour or \$23.59 per airplane

Appendix B lists an alternate water cost calculation methodology where water is mass-produced at the airport using commercial water conditioning equipment. In this scenario, the water costs for an industrial gas turbine engine were used.⁵⁴ For a large airport, such as Seattle-Tacoma, providing demineralized water to all commercial aircraft (non-regional jet), the water purification system would need to provide about 11,290,835 gallons per year. The water cost for such a system would be \$0.026 per gallon. Transportation cost is the major expense, costing \$12.28 per aircraft. For a 300 passenger aircraft this would result in a water cost of \$20.08 (300 gallons x \$0.026 + \$12.28).

4.4.9 System Cost

The additional system cost is estimated to be between \$100,000 and \$200,000 for each aircraft. This does not include non-recurring engineering costs. On a simple straight-line basis, the non-recurring costs are estimated to add approximately \$9,200 per aircraft.

4.4.10 Operating Economics

Table 4.4 shows the anticipated performance impacts on the aircraft for using combustor injection as well as LPC injection, both on a water saturated or cold (32F) day and standard day (59F) conditions.

Table 4.4. Performance Impacts for 777-type Airplane

	<u>Combustor Injection</u>	<u>LPC Inj. (cold day)</u>	<u>LPC Inj. (standard day)</u>
Mission length (nmi)	3,000	3,000	3,000
Trips per year	475	475	475
Incremental T/O fuel (lb./trip)	51	-56	-90
Incremental cruise fuel (lb./ trip)	63	63	63
Water used (gallon)	132	300	300
Range loss at 100% LF (nmi for MTOW limited)	80	80	80
(nmi for fuel tank limited)	7	7	7
Capital Costs	\$159,202	\$159,202	\$159,202
NOx reduction per LTO (lbs)	52.9	47.2	49.2

Table 4.5. Fuel, Water and Maintenance Costs for 777-type Airplane

	<u>Combustor Injection</u>	<u>LPC Inj. (cold day)</u>	<u>LPC Inj. (ave. day)</u>
ΔFuel cost per departure	\$5.45	\$-5.98	-\$9.61
ΔFuel cost for cruise (@ \$0.72/gallon)	6.73	6.73	6.73
Water cost @ 0.026\$/gal (per departure)	3.43	7.80	7.80
Water service cost (\$ per departure)	12.28	12.28	12.28
ΔMaintenance per departure	10.31	10.31	10.31
Simple capital cost (25 year life, 475 trips/yr)	13.41	13.41	13.41
Total Δ cost per departure	\$51.61	\$44.55	\$40.92

Table 4.6. Water misting NOx reduction cost

	<u>Combustor Injection</u>	<u>LPC Inj. (cold day)</u>	<u>LPC inj. (ave. day)</u>
Total Δ cost per departure	51.61	44.55	40.92
NOx emissions reduction (lbs. per LTO)	52.9	47.16	49.2
Emissions reduction cost (\$/ton)	\$1,951	1,889	1,663
(\$EU/kg)	2.56	2.48	2.18

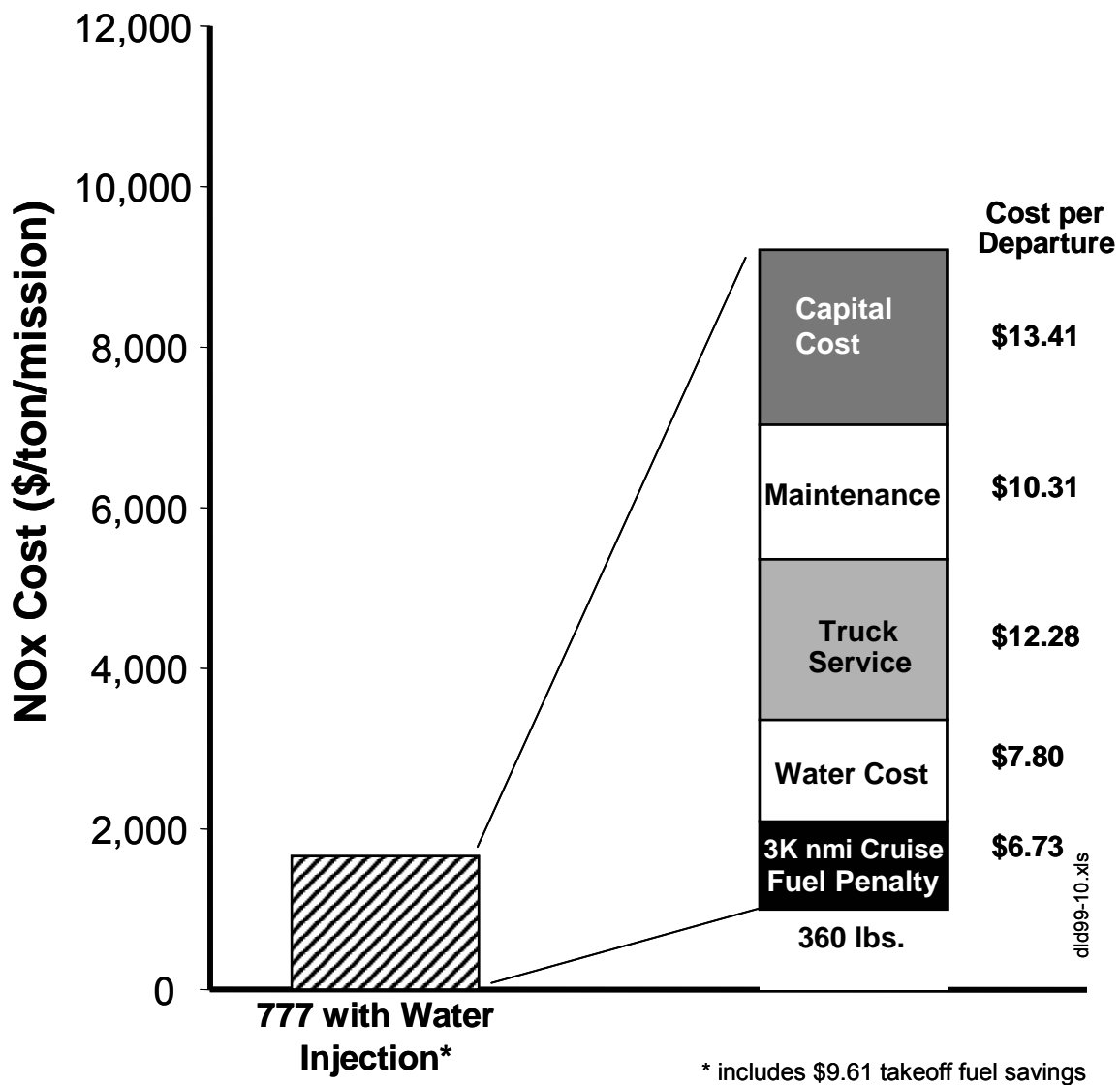
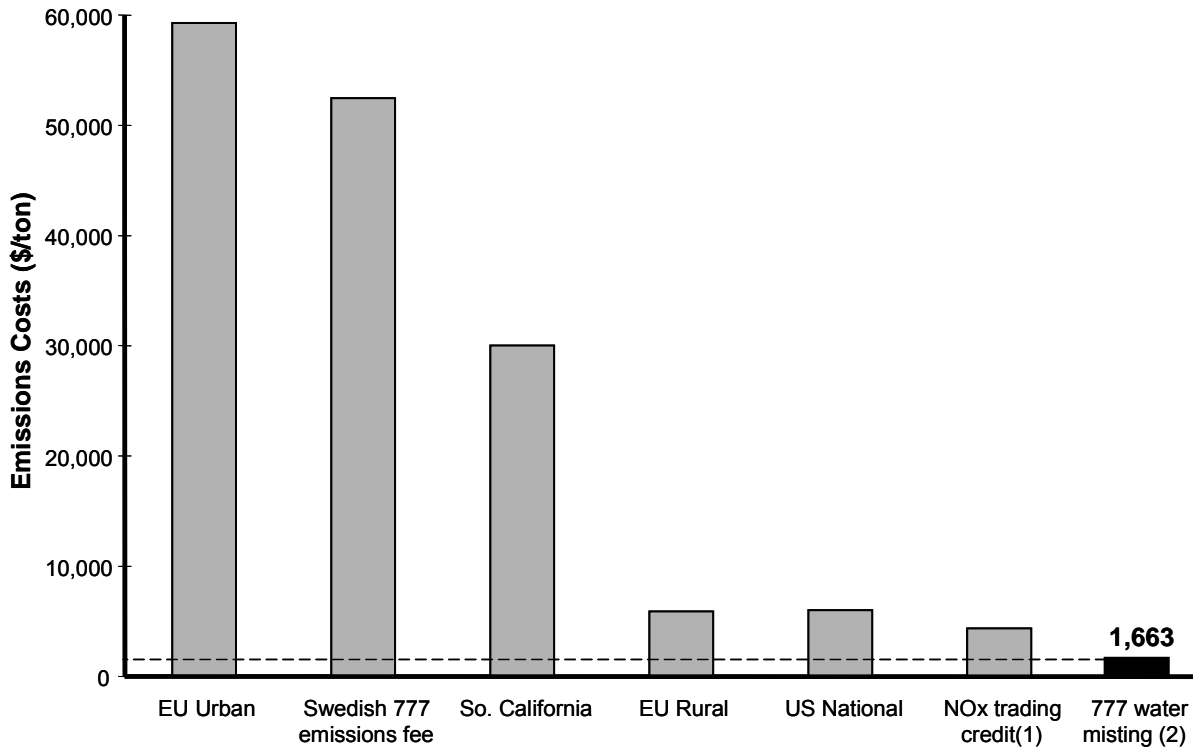


Figure 4.27. Cost breakdown of airplane water misting intercooler system.

Figure 4.27 shows the breakdown in water misting costs per takeoff and also shows the cost/benefit of the technology.

Figure 4.28 illustrates how the cost of the airplane engine water misting intercooler system compares with the costs that industry typically is paying for NOx reduction through various emissions reduction technologies. The chart also lists the cost/benefit ratio that airplane operators are subject to at Swedish airports by emissions-based landing fees. Thus, for the study airplane, the emissions cost/benefit ratio is very favorable. Other sized airplanes/engines will have different ratios, and in some cases (e.g. small airplanes with frequent stops) the cost/benefit ratio may be substantially worse.



Notes: 1) Typical emissions Trading Credit (RTC) in 1999.
 2) 777-200ER on 3,000 nmi mission

Figure 4.28. Large airplane engine water misting may prove to be substantially less costly than other industrial NOx reduction technologies.

4. 4.11 Airline Operator Survey

Nine airlines were surveyed about the use of water injection for NOx reduction. Only 2 responded. Both airlines indicated they had used water injection for their older 747 aircraft and both noted they had experienced added cost due to the requirement of obtaining demineralized water. One operator noted the water pumps would occasionally freeze. The other reported increased maintenance due to corrosion inside the water system. Based on their previous experience, neither airline welcomed the technology. However, one airline indicated that for a newly designed system, the previous technical difficulties would most likely be avoided. If hot section life could be increased, then they might be interested in the technology. A 3rd airline that did not respond directly to the survey but indicated that the technology would be of interest should airport emissions landing fees increase or operating restrictions come into place.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Results

Water injection has been used on industrial gas turbine engines for about 30 years to reduce NO_x emissions. Water injection was used on Boeing 707 aircraft (circa 1958) and early 747 aircraft (circa 1969) to increase thrust. This current study suggests that water injection can be used on new aircraft to reduce takeoff NO_x emissions at very competitive costs.

The study results showed that the newer water misting system, where atomized water is injected before the LP compressor, has a beneficial effect on engine performance and NO_x emissions. This is particularly true for operations on hot days. When water is injected prior to the HP compressor, NO_x emissions are equally reduced, but some fuel efficiency gains are lost. When water is injected directly into the combustion chamber, one will find a much improved reduction in NO_x emissions for the same amount of water. However, engine fuel efficiency suffers and turbine inlet temperature reduction is not as great as for the LPC injected system.

Based on a 305 passenger future technology airplane with current technology engines delivering 85,000 lb. thrust, an airplane operator would experience a 46.5% NO_x reduction and 3.5% SFC improvement on a 69F day during the takeoff and climb-out portion of the mission. This will avoid contributing 49.2 lb. of NO_x to the airport environment and save 90 lb. of fuel during the 3.3 minute takeoff and climb-out phase. 63 lb. of fuel would be required to carry the water misting intercooler support equipment on a 3,000 nmi. mission. For takeoff during days when the air is fully water saturated or below freezing conditions, NO_x reduction is still achieved by injecting water into the HPC, but the fuel efficiency improvements will be reduced to 1.7% as there will be no evaporative cooling experienced in the engine inlet and LPC. For a direct combustor injection system, an operator would experience a 2.0% decrease in fuel efficiency during takeoff. This is compounded by a 63 lb. fuel use penalty on a 3,000 nmi mission by having to carry 360 lb. of added equipment for the water injection system. However, much greater (e.g. 70-85%) NO_x emissions reduction potential could be achieved by combustor injection.

The cost effectiveness of the LPC water misting system appears to outweigh that of the other systems. From initial estimates, this system would cost the operator an average of \$40.92 per takeoff cycle for the 305 passenger study airplane. About 32% of this cost is due to the capital cost of the equipment, 25% for increased maintenance with the rest being accounted for by water and servicing costs.

Other potential savings for airplane operators were suggested in the study, though not analyzed, for improvement in engine hot section life. When using water misting injection, the turbine inlet temperature is expected to decrease

approximately 436 °R during the most demanding part of the airplane mission -- take off roll and initial climb-out. Industrial engines have experienced compressor blade erosion when using water misting continuously. If this system were used just for takeoff on aero engines, this erosion challenge may be turned into a cleaning opportunity. Clean compressors and turbines have been shown to restore from ½ to 1% of SFC. Analysis and test work would be required to understand these effects and validate the potential benefits.

5.2 Analysis of Results

European airports in England, Sweden and Switzerland are, or will be, charging airport landing fees based on airplane LTO emissions. For a 777-200ER airplane (636.5K MTOW) using a P&W non-water misted engine, the emissions penalty portion of the landing fee in Sweden would be \$537.00. A certain amount of NOx emissions from each “clean” airplane is permitted at the airport. If one looks at the penalty cost (i.e. \$537.00) of the NOx emissions beyond the allowed “clean” amount, this adds up to costing \$52,455/ton for the additional NOx emitted. This is substantially more than the estimated \$1,663/ton cost for the water misting NOx reduction technology studied in this report.

If the water misting injection system did indeed contribute to engine cleaning, the ½-1% fuel savings would more than offset the water injection cost on missions of 3,000 nmi or more.

Engine hot section components are very expensive and have shortened life with very high operating temperatures. With the reduction in turbine operating temperature during takeoff, there may be an opportunity to improve engine hot section life and reduce operator costs. However, these potential cost savings were not able to be quantified in the study.

As both of the water injection and water misting systems have the capability to increase thrust, taking advantage of this potential during critical event episodes (e.g. hot-day single engine-out) may have a safety benefit.

Although many questions remain, as evidenced by the feedback shown in Appendix C, the study suggested the technology may be able to offer performance and cost improvements over older style water injection. This could provide a very cost competitive reduction in airport NOx emissions to enable the continued growth of aviation.

5.3 Cost Uncertainties

An early draft of this high-level report generated much discussion amongst the engine and airframe manufacturers. Many uncertainties, that could impact the \$1,663/ton NOx reduction cost/benefit ratio, were suggested. Among them are:

- The study did not reiterate the study airplane design to use water injection only to 3,000 ft. (the 300 gallons of water ran out at 3,560 ft. in this study and gave more NOx reduction than for a 3,000 ft. altitude design)

- Engines with lower pressure ratios would benefit less from water misting.
- Smaller aircraft will probably have higher water misting operating costs.
- Combustor water injection will offer a greater degree of NO_x reduction. A tradeoff study with different water injection rates will highlight the best cost/benefit ratio for each technology and determine which is the better option.
- As range is slightly reduced with the technology, a new airplane with higher MTOW (to recover range) would suffer from increased landing fees.
- Increasing the number of takeoffs per year for large airplanes could reduce the operating cost.

Given these uncertainties, the GE Aero Engine group has suggested that costs could range from a low of \$1,297/ton to a high of \$8,380/ton of NO_x reduced. If the water service costs could be reduced, as suggested by the CH2M group, these costs could be cut in half. Should the water wash benefits to SFC prove real, the costs would be cut to nil. Further, T4 reduction benefits and resulting hot section life improvements could conceivably turn water misting costs into savings for the airlines.

5.4 Recommendation

As this study only offered a “quick look” at the cost and benefits of different water injection methods, a more in-depth analysis is needed. Aerospace engine companies, airplane manufacturers, NASA and government organizations together need to further evaluate this technology and identify the steps necessary to bring such technology to maturity for commercial airplane application.

Issues (both bad and good) that need to be addressed are listed: impact on engine hot section life, engine high pressure compressor operability issues, impact of the technology to smaller and larger aircraft/engines, range of cost/benefits due to uncertainty, emissions prediction validations (including soot) with actual test results, safety analysis, find the optimum balance between water misting rate and NO_x reduction (e.g. 50% or 85% NO_x reduction), airplane range tradeoff issues, possible compressor cleaning effects, water droplet size, LPC water misting vs. combustor water injection architecture determination, evaluate system weight reduction opportunities and lastly, water misting benefits to very high pressure ratio engines (e.g. UEET powerplants with OPR of 60-70).

This NO_x reduction technology appears to offer attractive enough benefits that it merits further, more in depth investigation.

APPENDIX A. NOX CALCULATION METHODOLOGY

The NASA NEPP code used an equation to predict the NOx emissions at any given power setting, based on the engine's T3 and P3 conditions (Equation 1 in section 2.2.1). The NASA NEPP data is not intended to replicate any particular engine, but it does reflect anticipated GE90 and PW4000 types of engine performance. For the combustor emissions data, the NASA NEPP NOx code attempted to mimic GE90-type of engine performance. In order to validate the NASA equation, two steps were taken; 1) the NASA predicted NOx was compared to ICAO engine test data points, and 2) the NASA NOx equation was used with Boeing GE90-85B proprietary engine performance data to predict NOx

For step one, the NASA emissions code closely predicted EINOx numbers for the four ICAO LTO measurement points (takeoff, climbout, approach and idle.) However, it does not confirm the under laying basis for the EINOx prediction -- T3 and P3 data points.

The next step was to see how closely the code predicts EINOx given that actual engine performance points (i.e. T3, P3) are used. Using Boeing GE90-85B engine performance data and the NASA NEPP EINOx equation, Figure A-1 illustrates the differences between the NASA EINOx equation prediction and actual test data recorded in the ICAO data sheets. Results from the NASA NOx equation are shown in the down-ward sloping line, given Boeing T3, P3 and thrust inputs for the GE90-85 engine. The two ICAO data points for this engine (ID # 3GE064) are shown for 100% (takeoff) and 85% (climb out) thrust levels. There is a 10.58 EINOx difference between takeoff and climb using ICAO data points. However, the NASA equation predicts a 7.95 EINOx difference, underpredicting the NOx reduction by 7.4% when at the 85% power setting and 35.7 EINOx point. Therefore, when engine T3 levels are reduced while using water misting injection, a greater NOx reduction may occur than was predicted by the NASA NEPP code.

For the purposes of this high-level study, these levels of NOx accuracy are within reason. Further improvements in the emissions accuracy prediction would require disclosure of proprietary engine data and is outside the scope of this study.

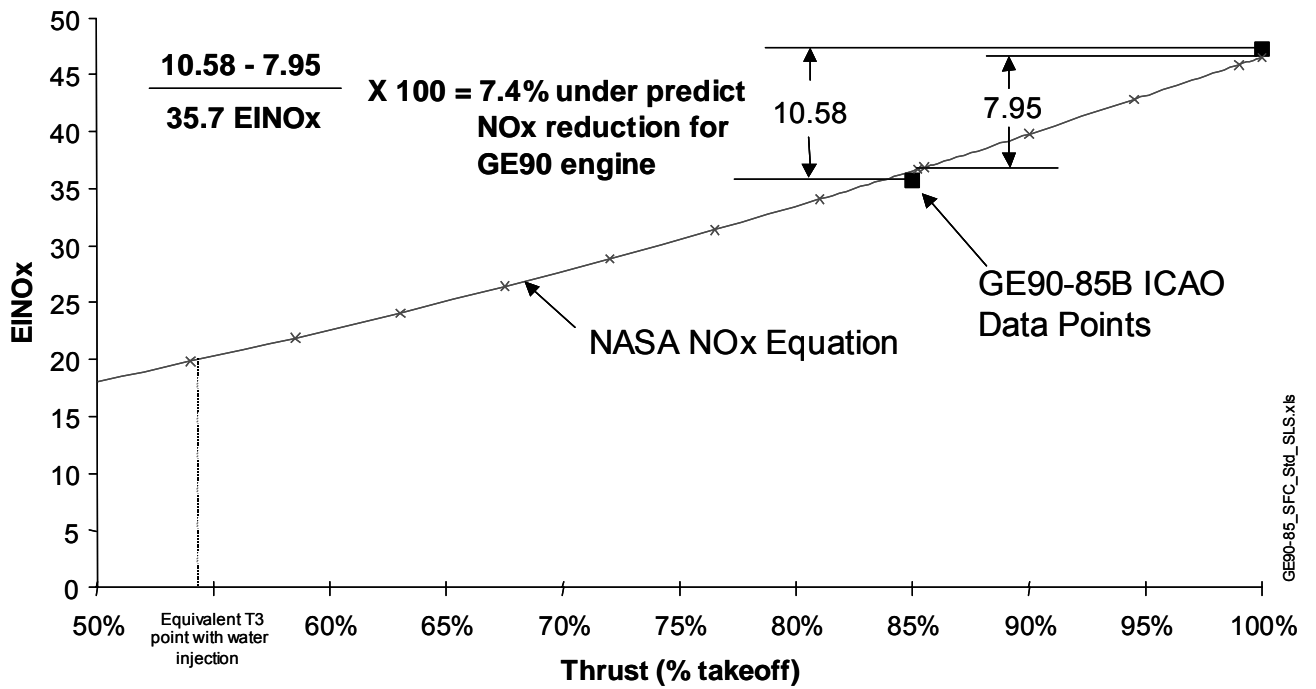


Figure A-1. Using Boeing GE90-85B engine data, the NASA NOx equation under predicts NOx reduction potential by 7.4% at the 85% thrust level

APPENDIX B. COST ESTIMATION OF WATER INJECTION

Study Ground Rules

In this investigation, the overall water conditioning costs for the entire commercial aviation fleet are estimated. Air traffic data for Seattle-Tacoma (Sea-Tac) international airport are used as a basis for the cost estimation.

The focus is on airplanes larger than 100 seats, which exclude regional services and commuters (representing almost half of Sea-Tac's air traffic volume.) It is anticipated that water injection will yield little value for regional airplanes.

Seattle-Tacoma International Airport Traffic 2002

The investigation is based on annual 2002 statistics and also for the month December 2002. Table B-1 shows all the Boeing, Airbus, McDonnell Douglas and Lockheed L-1011 aircraft that are included in the airport's statistics.

Figure B-1 illustrates a further breakdown of commercial aircraft, by type, for non-regional airplanes. By far, the highest percentage of aircraft at Sea-Tac are Boeing 737 aircraft.

Table B-1: Airplane Cycle Statistics SEA Int'l⁵⁵

	Dec/02	2002
Departures	9,247	113,910
Boeing	6,113	77,183
Airbus	1,187	12,203
Lockheed	6	101
MDD	1,941	24,423

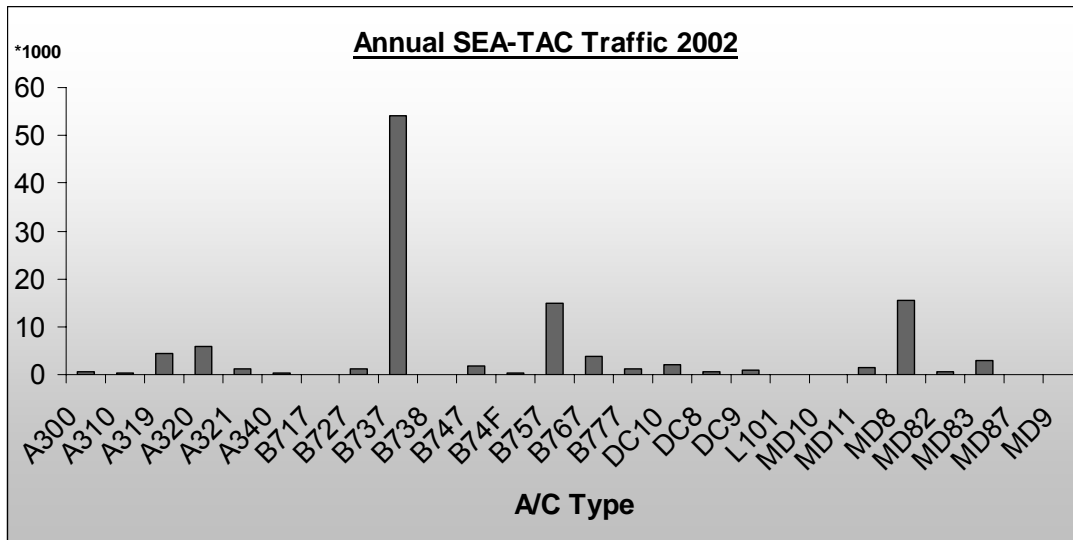


Figure B-1: Annual Traffic Seattle Tacoma International Airport 2002

Figure B-2 shows the monthly traffic at Sea-Tac for December 2002. The distribution is similar to the annual traffic shown in Figure B-1. Table B-2 shows the tabular data that was used to generate Figures B-1 and B-2.

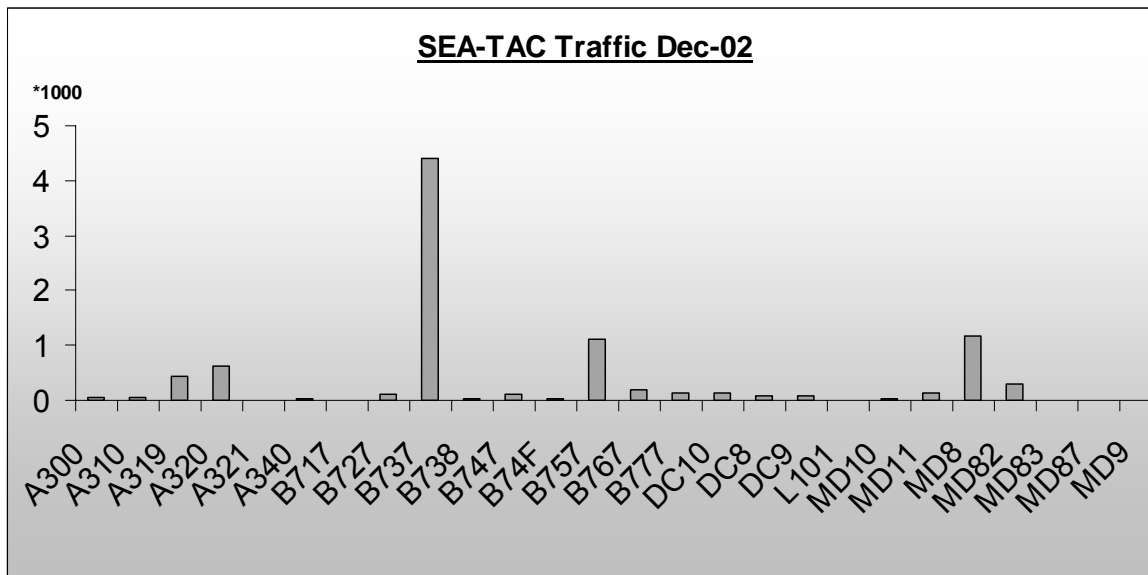


Figure B-2: Sea-Tac Traffic December 2002

Table B-2: Sea-Tac Traffic Statistics⁵⁶

Aircraft Model	Monthly Landings			Year To Date Landings		
	Dec-02	Daily Average	Market Share	2002	Daily Average	Market Share
A300	52	1.68	0.36	522	1.43	0.29
A310	50	1.61	0.35	204	0.56	0.11
A319	429	13.84	2.99	4,335	11.88	2.44
A320	628	20.26	4.37	5,833	15.98	3.29
A321	0	0	0	1,080	2.96	0.61
A340	28	0.9	0.2	229	0.63	0.13
B717	0	0	0	4	0.01	0
B727	99	3.19	0.69	1,047	2.87	0.59
B737	4,396	141.81	30.62	54,035	148.04	30.43
B738	30	0.97	0.21	122	0.33	0.07
B747	115	3.71	0.8	1,764	4.83	0.99
B74F	21	0.68	0.15	228	0.62	0.13
B757	1,122	36.19	7.82	15,046	41.22	8.47
B767	199	6.42	1.39	3,740	10.25	2.11
B777	131	4.23	0.91	1,197	3.28	0.67
DC10	125	4.03	0.87	1,993	5.46	1.12
DC8	74	2.39	0.52	667	1.83	0.38
DC9	88	2.84	0.61	903	2.47	0.51
L101	6	0.19	0.04	101	0.28	0.06
MD10	33	1.06	0.23	137	0.38	0.08
MD11	130	4.19	0.91	1,559	4.27	0.88
MD8	1,181	38.1	8.23	15,654	42.89	8.82
MD82	308	9.94	2.15	610	1.67	0.34
MD83	0	0	0	2,848	7.8	1.6
MD87	2	0.06	0.01	48	0.13	0.03
MD9	0	0	0	4	0.01	0
Total	9,247	298.29	64.43	113,910	312.08	64.15
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In order to estimate the water requirements for all aircraft, the Boeing 777-200 is used as the basis for further calculations. Depending on thrust of both engines for each airplane type, the required amount of water per aircraft type will be determined. Assuming the 777 has an average thrust rating of 390,000N (87,660 lb.) per power plant or 780,000N (175,320 lb.) per airplane and a water reservoir of 300 gallons, the water amount per Newton (lb. thrust) can be determined.

This is:

0.0003846 Gal/N, 0.3846 Gal/kN or
 0.00171Gal/lb thrust

Based on these average values, the total amount of water required for each airplane can be determined from its thrust. Figure B-3 shows the estimated amount of water that would be required for each airplane type using the above equation.

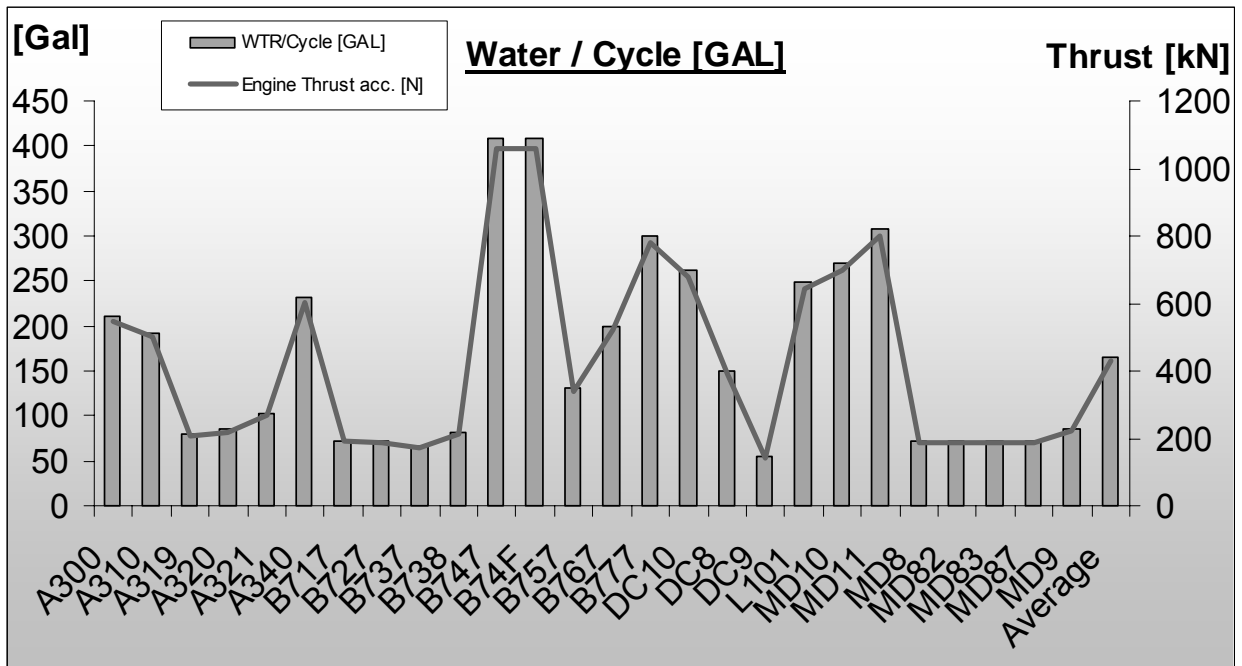


Figure B-3: Water required per cycle and thrust for various aircraft types

Having determined the amount of water per cycle and knowing the total cycles performed at Sea-Tac airport in 2002, the total required water for the airport is calculated for the December 2002 traffic as well as for annual traffic in 2002. Using the traffic data from Table B-2 and the water required data from Figure B-3, total amount of water required for Sea-Tac airport is:

902,436 Gal / month [DEC 02] or

11,290,835 Gal / year [2002]

Table B-3 shows the breakdown by airplane type and also shows the monthly and yearly average water consumption. This leads to an average daily requirement of 30,022.3 Gal and a maximum of 33,036.8 Gal per day.

Table B-3: Water amount determination

Aircraft Model	Engines	Engine Thrust [N]	Engine Thrust acc. [N]	WTR/Cycle [GAL]	WTR RQ Mth [GAL]	WTR RQ Yr [GAL]	WTR RQ Day [GAL]	WTR RQ Day [GAL]	av [GAL]	max day rq [GAL]
A300	2	273000	546000	210.0	10920	109620	352.3	300.3	326.3	352.3
A310	2	250000	500000	192.3	9615	39231	310.2	107.5	208.8	310.2
A319	2	104500	209000	80.4	34485	348467	1112.4	954.7	1033.6	1112.4
A320	2	110000	220000	84.6	53138	493562	1714.1	1352.2	1533.2	1714.1
A321	2	133000	266000	102.3	0	110492	0.0	302.7	151.4	302.7
A340	4	151000	604000	232.3	6505	53198	209.8	145.7	177.8	209.8
B717	2	95000	190000	73.1	0	292	0.0	0.8	0.4	0.8
B727	3	62300	186900	71.9	7117	75263	229.6	206.2	217.9	229.6
B737	2	86000	172000	66.2	290812	3574623	9381.0	9793.5	9587.3	9793.5
B738	2	107000	214000	82.3	2469	10042	79.7	27.5	53.6	79.7
B747	4	265000	1060000	407.7	46885	719169	1512.4	1970.3	1741.4	1970.3
B74F	4	265000	1060000	407.7	8562	92954	276.2	254.7	265.4	276.2
B757	2	170000	340000	130.8	146723	1967554	4733.0	5390.6	5061.8	5390.6
B767	2	260000	520000	200.0	39800	748000	1283.9	2049.3	1666.6	2049.3
B777	2	390000	780000	300	39300	359100	1267.7	983.8	1125.8	1267.7
DC10	3	227000	681000	261.9	32740	522013	1056.1	1430.2	1243.2	1430.2
DC8	4	98000	392000	150.8	11157	100563	359.9	275.5	317.7	359.9
DC9	2	71000	142000	54.6	4806	49318	155.0	135.1	145.1	155.0
L101	3	215000	645000	248.1	1488	25056	48.0	68.6	58.3	68.6
MD10	3	233500	700500	269.4	8891	36911	286.8	101.1	194.0	286.8
MD11	3	266000	798000	306.9	39900	478493	1287.1	1310.9	1299.0	1310.9
MD8	2	93400	186800	71.8	84850	1124680	2737.1	3081.3	2909.2	3081.3
MD82	2	93400	186800	71.8	22129	43826	713.8	120.1	416.9	713.8
MD83	2	93400	186800	71.8	0	204618	0.0	560.6	280.3	560.6
MD87	2	93400	186800	71.8	144	3449	4.6	9.4	7.0	9.4
MD9	2	111300	222600	85.6	0	342	0.0	0.9	0.5	0.9
	2.5	166046.15	430623.08	165.62	902,436	11,290,835	29110.8	30933.8	30022.3	33036.8
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Water Quality

The quality of water used for water injection has to meet certain requirements to ensure minimum maintenance and maximum durability of the engines. Especially important is any water contamination with solids that can damage the engine turbine material and severely reduce engine life cycles.

The following water quality criteria were specified from GE:⁵⁷

- Total Na, K, Pb, Va and Li \leq 0.1 ppm,
- Total dissolved and nondissolved solids $<$ 5 ppm,
- Total suspended solids \leq 10 mg/Gal,
- Maximum size of solids \leq 20 μ m (absolute).

Regarding water treatment, special procedures are required to remove solids, etc. These are:

- Pre-treating water with a two bed cation / anion or reverse osmosis system
- Water treatment typical by a mixed bed deionizer.

Water Price Calculation

The following water price calculations are based on data given in reference 58. Water price is a function of several factors, ranging from daily fixed costs to variable costs dependant from the amount of water processed. The following is a list of these costs:

1. purchase price of the plant (amortization, Tax 8%)
2. plant maintenance
3. labor costs
4. electricity
5. raw water
6. chemicals
7. disposal
8. transport to A/C

The focus of the following calculations is to determine of the price of conditioned water per gallon. The cost data given in (58) are for the year 1989, so a cost price increase from 1989 to 2003 has to be recognized. Using the US consumer price index, a 47.1% price increase is figured to have occurred in the past 14 years. Using the maximum daily water requirement of 33,036 gallons for Sea-Tac airport, the following water condition and cost estimations are made:

1. The purchase price of the plant is given in (58) as \$357,000 for a 20 Gallon Per Minute (GPM) output. According to the Sea-Tac example, an average 22.94 GPM are required, which is 14.7% more than the \$357,000 plant example. As the water demand may vary extremely

during the peak hours, a large storage tank will be needed to ensure water availability during the entire day. Figuring in price inflation (47.1%) and increased water output requirement (14.7%), the estimated cost of the water treatment plant is:

$$\text{Purchase Price} = \$ 357,000 * 1.147 * 1.471 = \$ 602,343$$

$$\text{Sales tax WA (8\%)} = \$ 48,187$$

$$\text{Unit Price} = \$ 650,531$$

Amortization of the plant is assumed to run over 15 years. On a simple straight-line basis, the capital cost per day is:

$$\text{Amortization costs} = \frac{\$650,531}{15 \text{ yrs} \cdot 365 \text{ days}} = \$ 118.82 \text{ per day}$$

2. Plant Maintenance is given as 10% per year of the purchase price, which can be easily transferred to daily fixed costs..

$$\text{Daily maintenance} = \frac{\$650,531 \cdot 0.1}{365} = \$ 178.23 \text{ per day}$$

3. Labor is required to maintain water quality and ensure standards. Labor costs are based on 4 hours manned supervision per day, labor cost is based on \$20.00 per hour (including benefits) in 1989. Including the price index increase of 47.1%, labor costs are $\$20 \cdot 4 \text{ hrs} \cdot 1.471 = \$ 117.68$ per day.

Fixed costs from above (1. to 3.) can be summarized as \$414.73 per day.

The following calculations are based on an average daily water production rate and will vary depending on the actual amount of water produced.

4. Electricity usage is given as 2,060 kWh / day for a 20 GPM production rate. Considering a technology improvement in the electrical motors, pumps and overall system efficiency has probably occurred in the last 14 years, an improvement of 20% is assumed in the calculations. Electricity costs are estimated to be \$0.05/kW. Thus, the required electrical energy is estimated to be:

$$\text{Total kWh} = \frac{0.05\$/kW \cdot 2,060 \text{ kWh} \cdot 1.147 \cdot 0.8}{33,036 \text{ gal} / \text{ day}} = \$ 0.00286 \text{ per gallon}$$

5. Raw water price is given as \$ 1.18/1000 gallons. One third of the raw water remains as wastewater and has to be disposed. Only two thirds are usable portions of the original amount. Considering a water output of 33,036 gallons/day, 49,554 gallons of raw water are required in the beginning of the process which results in a total price of:

$$\text{\$1.77/1,000 gallons treated water (output) or } \$ 58.47/\text{day (} \$ 0.00177/\text{gallon).}$$

6. Chemical usage is divided in H₂SO₄, HCl and NaOH. The Chemicals are used for every regeneration of resin packing. The required amount is 60 lb of 30% HCl and 33.5 lb of 100% NaOH. H₂SO₄ is required in a 5 lb./day volume for resin regeneration in deionizer. These numbers apply for a 20 GPM water output plant and have to be adjusted to the 22.94 GPM output.

This is 60.82 lb HCl, 38.42 lb of NaOH and H₂SO₄ of 5.74 lb./day.

The prices of each chemical are given on a 1989 level as:

- H₂SO₄ = \$ 0.22/lb.
- HCl = \$ 0.08/lb.
- NaOH = \$ 0.22/lb.

According to a 47.1% price index increase from 1989 to 2003 the updated prices are:

- H₂SO₄ = \$ 0.324/lb.
- HCl = \$ 0.118/lb.
- NaOH = \$ 0.324/lb.

Applying the updated daily usages, the following daily costs occur:

- H₂SO₄ = \$ 0.324/lb * 5.74 lb = \$ 1.860/day.
- HCl = \$ 0.118/lb * 60.82 lb = \$ 7.18/day.
- NaOH = \$ 0.324/lb * 38.42 lb = \$ 12.45/day.

As costs per gallon are used in the report, the sum of all three chemicals is \$21.49 per day divided by the daily volume of 33,036 gallons of water produces the costs per gallon of:

Chemicals per gallon = \$ 0.0006505 per gallon water produced

7. Brine Hauling and disposal is necessary as the plant produces 1 gallon of wastewater for each 2 gallons of cleaned water. Thus, the wastewater is 16,518 gallons per day. Assuming an 8,000 gallon tank capacity of a truck would make a wastewater disposal trip twice per day. The costs per mile of the truck are assumed to be \$ 0.45 per mile in 1989, thus \$0.662 in 2003 (47.1% increase). Depending on the location, a 200 mile trip is taken as average, producing costs of \$ 0.008015 per gallon. Alternately, disposal of the brine into an existing airport industrial waste water treatment plant would generate a cost. For this study, it will be assumed this cost would be equivalent to the aforementioned trucking costs.

The fixed cost data provided in numbers 1 to 3 above have to be broken down into costs per gallon of conditioned water. To determine this cost, the fixed costs are divided by the daily water production of 33,036 gallons for the example Sea-Tac airport:

1. Installation Costs: \$ 118.82 /day = \$ 0.003597 /Gal,
 2. Maintenance: \$ 178.23 /day = \$ 0.005395 /Gal,
 3. Labor: \$ 117.68 /day = \$ 0.003562 /Gal.
- Σ SUM = \$ 0.01255 /Gal

The variable costs per gallon can be calculated by adding numbers 4 to 7.

4. Electricity: \$ 0.00286 /Gal,
 5. Raw Water: \$ 0.00177 /Gal,
 6. Chemicals: \$ 0.0006505 /Gal,
 7. Disposal: \$ 0.008015 /Gal.
- Σ SUM = \$ 0.0133 /Gal

Adding the results of 1-3 and 4-7 leads to overall costs of \$ 0.026 per gallon. Figure B-4 shows the cost breakdown as well as the \$12.28 delivery cost to the airplane.

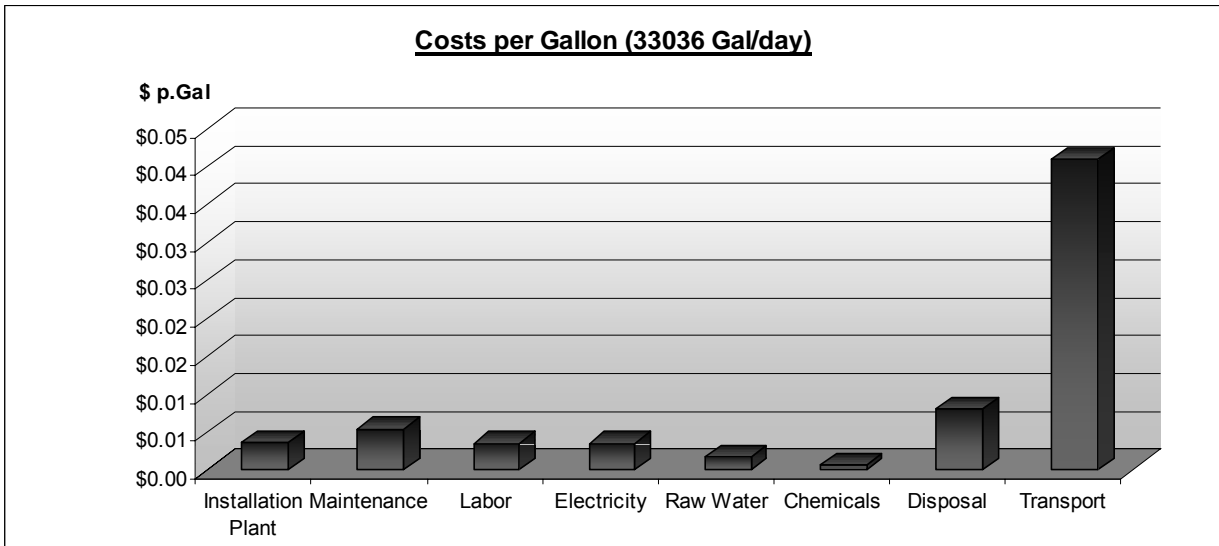


Figure B-4. Total Conditioned Water Cost

APPENDIX C. STUDY FEEDBACK

The draft report was issued to engineering, scientific and management staff at the Boeing company as well as GE, Pratt & Whitney and Rolls-Royce engine company staff. It was also issued to a company that specializes in providing water injection support systems for industrial engines. The following questions and comments were collected and answered (where feasible.)

Boeing Comments:

Comment: My initial impression on the SFC benefit for inlet misting was quite skeptical but it is reasonable based on simple fuel flow corrections using a lower "theta" value to account for evaporative cooling. The theta effect can also be used to imagine there will be a significant rematch if the core is inter-cooled but the fan is not. The report talks briefly about engine operability based on a thirty year old paper from P&W but the rematch effect may add a "new" dimension to this problem. For example, N2 rotor speed (along with SFC) would be reduced by nearly 3% for the 100 degF sample case where misting lowers core inlet conditions to 69 degF, but N1 would remain essentially unchanged.

Comment: Although there would be a high initial airport non-recurring cost, it would probably make sense to install a dedicated purified water line at each gate at the airport. Since the service cost is the highest part of providing the aircraft with purified water, this cost could be eliminated by having the ground service personnel refill the potable and purified water tanks at the same time.

Comment: The water injection system maintenance costs you listed in figure 4.27 should probably be reduced, or maybe even eliminated. We can do a lot better today than those old TWA numbers you quoted.

(author's comments: from the above two comments ... by eliminating the water delivery charge and reducing the system maintenance costs 80% would cut the operator costs of the system about in half [\$20.39/takeoff] and improve the cost/benefit ratio [\$832/ton] of the NOx reduced for this study airplane.)

Comment: An 80 mile decrease in range is not insignificant and needs to be addressed. A dollar value on this performance penalty number needs to be figured somehow and included in the cost/benefit analysis.

Comment: Adding more components to current installations will be a challenge. There isn't a lot of space available on current engines to add more components without impacting repair times in a negative way. The risk is that this new system will potentially block access to other systems on the engine/strut. If the installation blocks another system you suffer the penalty of having to remove water injection system components (lengthening repair times and potentially inducing damage) when the blocked system has a failure requiring maintenance. The converse is also true, if the installation buries components of the water injection system, when it fails you may have to remove components not part of the water injection system (increasing maintenance time). Depending on which components

have to be removed and reinstalled, there may be an engine run required to verify proper system operation. Again, increased maintenance time and cost (fuel, additional engine wear).

Comment: A 400+ degree decrease in T4 is amazing. We might even see something like a doubling of turbine life with that kind of reduction.

Q: How many breaks/connections in the system are there? Every one of them is a potential site for leakage that negatively affects system operation and will require maintenance. There is the added problem of potential corrosion at each one of those sites.

A: The number of connections will be minimized where possible. One operator has reported corrosion problems in their water injected 747s. As the wing tanks have bladders, perhaps it is feasible that this corrosion could be coming from the water lines and connections.

Q: What method(s) will be used to determine if there is a system failure? Is it integrated with engine monitoring systems? Is it separate? Are there no diagnostics at all?

A: There is a water tank level gage and a water flow gage that will help with diagnostics. However, if a water line ruptured or leaked inside the wing there may be no way to determine this. The water would freeze and could cause problems with another system. A failure detection system needs to be addressed.

Q: If the system has a failure can the airplane continue to fly without any needed maintenance action required until a time is found to repair the system?

A: The system is designed to be operated at the discretion of the pilot and operator. That is, it doesn't need to be used for added thrust during takeoff. It is only for NOx control. However, if the system would fail with water still in the tanks, it must be serviced to remove the water. Existing water injection systems have not been affected by having a small amount of water remain in the tanks and pumps that froze up.

Q: What are the field length impacts of provisioning for the system not running and you have to complete the takeoff with 2,500 lbs of extra water? What if the system failed to drain? What are the operating cost impacts of these failures?

A: The study airplane did not take advantage of the potential additional thrust available and included 2,865 of added weight (2,505 for water and 360 for system), displacing that same amount of fuel weight, so there would be no impact on field length if the system failed. If it experienced a double failure (didn't drain) then the airplane would have to return to the airport. Double failure scenarios are generally not included in cost calculations.

Q: What is the impact of the small amount of extra thrust (or does the control throttle back to hold thrust constant?) Would this be allowed?

A: The study airplane kept the same thrust level when using water misting, so the engines would be throttled back slightly. Engine control scenarios need to be addressed by the engine companies.

Q: Although we think the range penalty is small, what happens to range/payload when you are trying to takeoff out of Denver on a hot day on a flight to JFK? Would it be impacted by having to plan for the extra water weight?

A: When the airplane is filled to 100% capacity and is range limited, perhaps the air quality authorities would allow takeoff without water injection for these infrequent episodes? Ironically, it is these instances where the added thrust from the water injection could be most used, but was not considered due to safety concerns if the system failed.

Comment: - You're adding a lot of water to the combustor and water is not inert at those temperatures. It will have some effects on the heat distribution and chemistry which may influence the other emissions. I would be concerned about how the water injection affects the fuel droplet dispersion and evaporation and in turn how that affects mixing/soot generation and combustor efficiency (i.e., CO and hydrocarbons) I suspect that water injection may increase hydrocarbon and soot emissions if it interferes with fuel droplet evaporation and fuel/air mixing. You're going to change the heat distribution in that region by injecting water and you don't seem to be addressing or even commenting on that in any way

Comment: You assume that the empirical T3/P3 relationships will work even though you have made major changes to the heat capacity and composition in the combustor. This makes me uncomfortable without some kind of analysis to support this assumption.

Comment: Note that while water injection has been used in stationary power plants, these are systems designed for single-point operation. For aircraft the combustor has to work over a much wider dynamic range. Water injection may be trickier, particularly since you want to inject water at the power settings that are most important for takeoff and safety of flight. What happens if the water system dumps too much water into the combustor? Fire goes out at the wrong time?

Comment: Reducing NOx at the expense of these other emissions [HC, CO, Soot], may or may not be a good trade.

Comment: In figure 4.25, you contrast CO generation for 2 engines (LM2500 and LM6000). Other than telling us CO may be a big problem, what does this figure tell us about how an aircraft engine would behave?

From CH2M Hill, Bellevue, WA (H₂O conditioning support company)

Comment: Water conditioning costs seem high. Without including transportation costs, Boeing comes up with 0.026 \$/gallons for conditioned water. Portable units on the market right now cost less than \$0.02 \$/gallon, which would be for the worst case scenario. For fixed base units, the costs would be around \$0.01 \$/gallon. However, this does not include brine disposal costs that would increase the cost.

Comment: Capital acquisition costs also appear high. Boeing quotes a \$650,531 capital acquisition cost. A comparable performance unit today costs about \$300,000. New Reverse Osmosis (RO) technology has dramatically brought down the cost of conditioning water from the days when the GRI report (that Boeing used as a basis) was written.

Comment: Water delivery costs, which make up the biggest portion of the water injection cost, might be brought down by installing piping throughout the airport. At the \$12.28 per service cost that Boeing figured, it probably wouldn't take long to pay off such a piping system at the airport. One needs to be careful to use either stainless steel piping (expensive) or plastic (affordable) to transport the conditioned water as other pipe materials can corrode very quickly when carrying this pure water. Another option might be to „piggy back“ onto the existing potable water delivery truck.

Comment: Maintenance time is too high. Today's water conditioning plants require a lot less maintenance than earlier generation plants. The 4 hours per day that Boeing quotes could probably be reduced to ½ to 1 hour per day.

Comment: For any next round of studies, it would probably make sense to look at several different sizes and types of airports as well as put more time into optimizing the water conditioning costs. This would make the study more realistic and would also probably result in lower water costs used to evaluate the overall cost of the technology.

Comments from GE Aero Engine Group:

The Boeing Draft Report on Commercial Aircraft Water Misting and Injection is an interesting and reasonably comprehensive initial evaluation of water injection. As a general comment, the cost/benefit numbers stated in the draft report may be overly optimistic. As discussed in our comments below, factors such as the potential usable range of water-to-fuel ratio, airplane size, effective cost of lost payload/range capability and landing charges are not fully considered in the initial cost/benefit analysis.

Water injection may be effective for low altitude operations, but it cannot be expected to address cruise emissions. In the case of the advanced 777 studied in the draft report, ~2500 Lb of water was required to reduce NO_x by 46.5% during the first few minutes of each flight. Since the water would be expended at the start of flight, impact on mission fuel consumption appears to be acceptable in most cases, but it would be impractical to carry enough water for cruise. Therefore, low

emissions combustors will still be needed to reduce NOx at cruise. Water injection and application of low emissions combustor technology could be complementary. Water injection could be used at takeoff, where the combustor inlet conditions make it most difficult to apply low emissions technologies, and the combustor could be optimized to reduce NOx at cruise.

In the case of an aircraft on a maximum range mission, it might be necessary to depart without water injection in order to safely meet the mission range requirement.

In the past, emissions reduction has been considered to be primarily an engine issue. With water injection, the responsibility for emissions reduction is shared with the airframe (water tanks and pumps) the airline (operation and maintenance of the system) and possibly the airport (treated water infrastructure). A complete evaluation of water injection for reduction of NOx emissions must consider engine technology, airframe requirements, servicing operations and infrastructure. The draft report covers all of these aspects for one aircraft application, the advanced 777. While recognizing that there could be major issues with respect to airframe, servicing and infrastructure, GEAE comments will focus on engine technology, our primary area of expertise.

Safety – Any approach to reduce emissions must be proven to be safe. Intuitively, spraying water into a fire suggests the possibility that the fire will be extinguished. The added complexity and servicing requirements of a water injection system also provide new opportunities for system reliability issues that could affect critical takeoff operations. The draft report describes previous experience with water injection, so safety issues have presumably been addressed. GEAE does not have experience with water injection in commercial engines, and we believe that a thorough system failure analysis must be completed before we could agree that water injection is an acceptable alternative for aircraft emissions reduction. Some risks that come to mind include:

- Water pump failure - Is there another way to empty the tanks? How much would range be reduced? Would water freezing in tank cause damage?
- FOD from water injectors in combustor or compressor
- Excessive water injection rate - Can it cause thrust loss?
- System leakage or backflow into water tank – Water injectors are in communication with fuel and combustor inlet air at >1200F and >600psi
- Icing would be a particular concern with compressor injection – If alcohol was used to prevent icing, most would bypass the combustor and be emitted as HC.

NOx Reduction May Be Overstated – The NOx reduction values calculated in the section on performance impacts (Table 4.3) and carried over into the discussion of NOx reduction cost (Table 4.4) is 49.2 Lb. NOx per takeoff. The ICAO data bank indicates total NOx emissions for two GE90-85 engines to be 107 lb for the ICAO LTO Cycle. Of the total, about 81 Lb. is produced at takeoff and climb conditions where water is injected. Based on that figure, at 46.5% NOx reduction, the total amount of NOx reduced would be about 38 Lb. Additionally, the

ICAO LTO cycle is somewhat conservative with respect to NO_x emissions because a modern twin-engine aircraft will typically operate at derated thrust, and will climb faster than assumed by the LTO cycle. This will probably reduce the typical in-service benefit by another 25%, to about 29 Lb. Assuming the costs are correct, this reduction in NO_x benefit would increase the cost from \$1,663 to \$2,800 per ton of NO_x reduced.

NO_x Reductions Relative to Cost Based on 777 Aircraft May Not Be Typical of The Fleet - The engines that power the Boeing 777 aircraft operate at much higher pressure and temperature most than other engines in service. The result is that NO_x emissions are high relative to other engines. For example, the NO_x emissions index for the GE90-85 at the ICAO takeoff operating condition is 47.28g/kg (Figure 4.20), nearly twice as high as the value of 25.30 g/kg for a CFM56-7B24 that is used on a 737. Since the NO_x reduction benefit is roughly proportional to the NO_x EI, the benefits might be reduced by nearly 50% in the 737 (thereby doubling the Cost/Benefit ratio). To provide a balanced perspective, cost and benefit numbers should be estimated for the 737. This is an important consideration because narrow body aircraft are major contributors to NO_x emissions (resulting from the large number of narrow body aircraft and the tendency to conduct more operations per aircraft per day). On the cost side, cost per unit of NO_x emissions reduced will tend to be increased for smaller aircraft because some costs (e.g. water servicing cost) are not dependent on aircraft size.

Status of Compressor Water Injection Technology – Compressor water injection for industrial engine performance enhancement has only been applied over the past few years. Therefore, there are still some issues that might still have to be addressed (e.g. water injector life, compressor erosion) with respect to long-term operation.

Compressor Water Injection Rate – In industrial applications, the draft report indicates that there is experience with injection rates between 0.5 and 0.87% of core airflow on 90F days. The 2.2% rate assumed for aircraft applications in this study would appear to be well beyond industrial engine experience. Potential effects on compressor erosion, NO_x emission reduction effectiveness, effect on other emissions, icing and engine stability would have to be considered.

Status of Combustor Water Injection Technology – Combustor water injection for NO_x reduction has been in use in ground based industrial engines for over 15 years.

Combustor Durability - Initial combustor durability issues due to water erosion have been addressed, and continuous operation with water injection for over 20,000 hours has been achieved in some cases. Therefore, based on total injection time, reduced durability with aircraft water injection would not be expected to be a major issue; however, there could still be issues with cyclic (LCF) life in aircraft applications.

Range of Operation - Water injection has been used in industrial engines derived from CF6-6, -50, and -80C aircraft engine designs. It has been used successfully over a moderate range of engine pressure ratio and turbine inlet temperature. Effectiveness in very high pressure and temperature engines such as those used on the 777 would still have to be demonstrated. NO_x reduction is not expected to be a barrier, but tradeoffs with CO might be significant in such applications.

Turbine Durability - Reduced turbine inlet temperature with water injection could significantly improve hot section durability.

Combustor Water Injection Rate – In industrial applications, combustor water injection has proven effective in reducing NO_x emissions by up to 90% at steady state operating conditions with water-to-fuel ratios of about 1.0. In some applications there is a tradeoff with CO emissions at this level. If the aviation industry took on the cost and complexity of water injection, there would be pressure to maximize the benefit by using a water-to-fuel ratio of 1.0. However, in order to provide margins for CO emissions and stability during aircraft operations (particularly rapid engine transients that might be required during takeoff and climb), it would be more prudent to consider limiting water-to-fuel ratios of about 0.7 in aircraft applications. This would still provide NO_x reduction of up to 75%. As indicated in the table below, this would also limit the water weight to about 1500 Lb., and constrain the tendency to increase CO emissions.

Compressor vs. Combustor Injection – The draft report seems to favor compressor injection (misting) based on improved engine performance and potential performance retention. However, combustor injection has advantages in that it can achieve greater NOx reduction, requires less water, and is based on technology that has been proven in long-term industrial service. The comparisons in Tables 4.3 and 4.4 of the draft report do not consider that with the smaller amount of water needed for combustor injection, the impact on payload/range capability is also smaller. Specifically, in Table 4.3 we estimate that the range loss for combustor injection (MTOW limited) should be about 42 nmi, compared to ~80 nmi for LPC injection.

Another way to compare the options is to assume that the potential of combustor injection to further reduce NOx (75% reduction) is used. A rough comparison between combustor injection for 75% NOx reduction to LP compressor injection for 46.5 % reduction is shown below.

Percent NOx Reduction	Base	0	50	75	85
Water to Fuel Ratio	0.00	0.00	0.35	0.70	1.00
Fuel Burn to 3000ft., Lb	2000	2000	2017.5	2035	2050
Weight of Additional Fuel	0	0	17.5	35	50
Weight of Water Tank and Pumps, Lb	0	360	360	360	360
Weight of Water	0.0	0.0	706.1	1424.5	2050.0
Total Water Weight Adder (lost payload), Lb	0.0	360.0	1083.6	1819.5	2460.0
Range Reduction, nmi	0.0	10.4	31.2	52.5	70.9
NOx Reduced, Lb	0.0	0.0	40.5	60.8	68.9
CO Increased, Lb	0	0	0	1.8	6
CO Increased, %	0.0%	0.0%	0.0%	6.3%	20.9%

	Combustor	LP Compressor
Percent NOx Reduction during Takeoff and Climb	75	47
Water to Fuel Ratio	0.70	1.02
Fuel Burn to 3000ft., Lb	2035	1910
Weights		
Weight of Additional Fuel (Relative to Baseline)	35	-90
Weight of Water Tank & Pumps, Lb	360	360
Weight of Water	1425	1940 *
Total Water System Weight Adder (lost payload), Lb	1820	2210
Range		
Range Reduction, nmi	52	64
Emissions		
LTO NOx Emitted, Lb	46	69
NOx Reduced, Lb	61	38. *
CO Increased, %	6%	0%

*Values of NOx emission reduction and weight of water from draft report reduced consistent with the total NOx reported on the ICAO data sheet.

With combustor injection, NOx emissions are reduced by 61 Lb, compared to 38 Lb with compressor injection. Even with this further NOx reduction, less water is needed with combustor injection, so the impact on payload is 290 Lb less than with LPC injection. Combustor injection is also based on more mature technology. There would be a slight increase in cost to account for 125Lb (~15 gal.) fuel use with combustor injection, and CO would be increased very slightly. Taking all of these effects into consideration the cost per ton of NOx reduced would likely be about 30% less with combustor injection than with compressor injection.

Increased Thrust with Water Injection - If water injection is used to reduce NOx emissions, there will be a temptation to use it for thrust augmentation. If this capability is used, water availability and water injection reliability become dispatch critical, and may have a greater impact on flight safety. Therefore, we agree with your view that studies should not count on water for thrust augmentation.

Costs – The simple cost estimates in the report should to be examined by the operators to confirm that all aspects of cost (e.g. spares, delays, lost payload/range capability, cost of money) have been considered. More detailed studies can also be expected to reveal unanticipated cost items. As an example, water injection to control NOx during typical reduced thrust operations will probably require more precise control of water flow than has been used for thrust augmentation, so control system costs will likely be higher than estimated in the draft report. Sensitivity of costs to assumptions such as aircraft utilization needs to be estimated. For example, GEAE would base cost estimates on ~640 trips/year, rather than the 475 trips/year assumed in Table 4.4. Utilization will vary depending on the operator, so it might be more useful to show a range of costs corresponding to a probable range of input assumptions.

Lost revenues due to reduced payload could far exceed all other costs associated with water injection. For example, on flights where range is critical, it would be necessary to displace cargo with water for NOx control. For ~50% NOx reduction, we estimate that this could result in lost revenue of \$720 (for combustor injection) to \$1285 (for compressor injection) for a 6000 nmi flight. This would not occur on every flight, but the impact should be considered.

One alternative to avoid lost revenue would be to increase MTOW to recover payload/range capability. This was studied in recent ICAO FESG analysis of proposed new NOx standards, where range was potentially reduced due to increased fuel consumption. FESG assumed that airlines would have to buy additional MTOW as necessary to maintain aircraft payload/range capability at a cost of \$217 per additional pound of MTOW (based on public price data). We estimate that it would require about 3000 lb additional MOTW with LPC injection to account for the weight of water, tanks, pumps and additional fuel. Based on FESG numbers, incremental airplane purchase price could increase by more than \$600,000. We believe that the actual costs would be somewhat lower, ranging from \$110,000 (combustor injection) to \$200,000 (LPC injection) for ~50% NOx reduction. Using the assumption that capital cost is spread over 11,875 departures (25 year life, 475 trips per year), this could add up to \$10 to \$50 per departure.

Additionally, FESG estimated a significant increase in operating cost due to increased landing fees that are based on MTOW. FESG used an international average value of \$4.50 per 1000 Lb of MTOW. At that rate, the 2500 Lb increase in MTOW would add another \$11 per departure. Independent GE estimates of incremental landing fees range from slightly more than \$5 (combustor injection) to slightly more than \$9 (LPC injection) for 50% NOx reduction.

Based on the above discussion, the cost per departure due to increased MTOW is potentially larger than the total delta cost of \$40.92 to \$52.90 estimated in Tables 4.4 and 4.5 of the draft report. This could more than double the cost per ton of NOx reduced.

Comments from Pratt & Whitney:

1) This is a very good and timely feasibility study. It shows that there is a significant potential benefit of NOx reduction by water injection. It also shows that from an airplane/engine system point of view, carrying water is feasible and may be cost effective. However, while it may be argued by some that water misting is cheaper than expensive combustors, past history with water injection has proven that adding water is more expensive than not adding water. There may be efficiency gains and NOx reductions, but the impact of adding water to short, high intensity combustors must be ascertained.

2) As the study points out, there are several options for adding water with varying and adverse system impacts. The impact on compressor surge margin has been mentioned, but no serious study has been conducted to quantify it. This may be a show stopper for introducing water before the HPC.

3) Where and in what quantity the water is added will also depend on the combustor design and the system will have to be optimized taking that into account. The history of water injection in aircraft engines is based on rich front-end combustors. The study implies, although not explicitly states, that future combustors will be lean front-end. We do not have any history with those combustors in aircraft engines. It is also not a forgone conclusion that all future combustors will be lean front-end.

4) Pratt & Whitney has developed expertise in NO_x reduction with water injection in aero-derivative engines for industrial application with rich front-end combustors. P&W has demonstrated the capability to reduce NO_x by a factor of 10X in industrial applications.

5) If Boeing proceeds with further conceptual studies to demonstrate the viability of water injection to reduce NO_x in aero engines, Pratt & Whitney would be willing to work with Boeing and a partnership of other engine companies to design and develop an aircraft/engine system.

6) It appears that business case development costs are based on lean staged combustors. The development costs associated with RQL technology must also be assessed.

7) Impact on CO emissions of rich and lean concepts must be assessed.

8) Water injection will increase engine thrust, hence the potential benefit to fuel burn (CO₂) that may occur during take-off and climb needs to be assessed.

Overall, the final report of the Boeing study on water injection is well done as far as performance, emissions and system design are concerned. The concern is that the operability issues with regard to water injection are treated in only a minimal fashion. Two major areas of concern are not adequately addressed. First, that of water droplet size and second, that of HPC stability changes due to water injection. These two areas are major drivers in the success or failure of the water injection system and should be further addressed in the report, or the overall conclusions are too easily accepted as easy opportunities [author's note -- further information on HPC operability effects are contained in P&W's operability memorandum WTC-04001 from William T. Cousins dated 1/16/04]

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13. ABSTRACT (Maximum 200 words) This report provides the first high level look at system design, airplane performance, maintenance, and cost implications of using water misting and water injection technology in aircraft engines for takeoff and climb-out NO _x emissions reduction. With an engine compressor inlet water misting rate of 2.2 percent water-to-air ratio, a 47 percent NO _x reduction was calculated. Combustor water injection could achieve greater reductions of about 85 percent, but with some performance penalties. For the water misting system on days above 59 °F, a fuel efficiency benefit of about 3.5 percent would be experienced. Reductions of up to 436 °F in turbine inlet temperature were also estimated, which could lead to increased hot section life. A 0.61 db noise reduction will occur. A nominal airplane weight penalty of less than 360 lb (no water) was estimated for a 305 passenger airplane. The airplane system cost is initially estimated at \$40.92 per takeoff giving an attractive NO _x emissions reduction cost/benefit ratio of about \$1,663/ton.				
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