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Engine Company Evaluation of Feasibility of Aircraft Retrofit Water-Injected Turbomachines

Arthur Becker
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April 2006

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1.0 Summary

This study supports the NASA Glenn Research Center and the U.S. Air Force Research Laboratory in their efforts to evaluate the effect of water injection on aircraft engine emissions. In this study, water is only injected during the takeoff and initial climb phase of a flight. There is no water injection during engine start or ground operations, nor during climb, cruise, descent, or landing. This study determined the maintenance benefit of water injection during takeoff and initial climb and evaluated the feasibility of retrofitting a current production engine, the PW4062 (Pratt & Whitney, East Hartford, CT), with a water injection system. Predictions are based on a 1:1 water-to-fuel ratio, and NO_x emissions for the current PW4062 (Pratt & Whitney, East Hartford, CT) at this ratio is likely to be reduced between 30 to 60 percent in Environmental Protection Agency parameter (EPAP).

The maintenance cost benefit for an idealized combustor water injection system installed on a PW4062 engine (Pratt & Whitney, East Hartford, CT) in a Boeing 747–400ER aircraft (The Boeing Company, Chicago, IL) is computed to be $22 per engine flight hour (EFH). Adding water injection as a retrofit kit would cost up to $375,000 per engine because of the required modifications to the fuel system and addition of the water supply system. The turbine must be matched for the increased flow to recover compressor surge margin, but it is assumed the kit will be incorporated at a major engine overhaul that includes replacement of the turbine airfoils, so no additional cost will be incurred. The combustor must undergo significant development to meet all system operability and performance and emissions requirements. Major nonrecurring expenditures (~$50 million) will be required to make the system retain acceptable stability margins in the high- and low-pressure compressors (HPC and LPC), to upgrade the engine control system for water-on takeoff power setting curves, and to certify the complete package. Recurring costs to the operator will be seen in reduced efficiency and in the cost of maintaining the water system. Thus, a retrofitted water injection system is technically feasible (it can be designed, installed, certified, etc.) but is not likely to be financially acceptable.

Note that adding a water injection system to a new engine in the design phase should eliminate much of the nonrecurring cost, reducing it from ~$50 million to ~$10 million, because the testing and certification would be conducted concurrently with the base engine. The recurring cost per engine would also be decreased because the fuel nozzles would not need to be replaced. As an option package, the kit is estimated to cost $250,000 per engine.

2.0 Introduction

A recent NASA contractor report[1] showed the feasibility of injecting demineralized water into the combustors of modern fanjets or into the LPC during takeoff to lower NO_x emissions by anywhere from 50 to 90 percent and reduce noise 0.61 dBa. The study suggested that smoke emissions may be positively impacted and that engine hot-section life could also be improved due to the estimated 436 °F decrease in turbine temperature.

NASA quoted that a >25-percent reduction in maintenance cost and 7-percent improvement in operating cost could be achieved by using water injection on a tiltrotor aircraft.[2] These two aspects are

[1]Daggett, David L.: Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport NO_x. NASA/CR—2004-212957, 2004.
[2]Eames, David: Short Haul Civil Tiltrotor Contingency Power System Preliminary Design. NASA/CR—2006-214059, 2006.

further explored in this study of large turbofan engines for a large commercial transport aircraft. In addition, retrofitting existing aircraft with this technology has the potential to lower aircraft emissions at airports and could simultaneously reduce aircraft operating cost.

In this report, the feasibility of a water injection system installed on a PW4062A engine (Pratt & Whitney, East Hartford, CT) is evaluated. The performance of the engine with water injection is predicted in terms of selected engine pressure and temperature simulations; the impact on the low- and high-pressure compressor (LPC and HPC) operating lines is also predicted. The effect of water injection on the NO_x emissions is also discussed. Next, the improvement in the airfoil durability is examined. This is followed by a section looking at the effects of water injection on maintenance costs. An overview of the different ways and places in the engine water injection could occur is presented, and the effect of the resulting rematches between compressor and turbine on performance and cost is investigated. The various engine systems that would need to be further studied before installation of a water injection system are listed. The suppression of noise upon incorporation of a water injection system is also described. At the end of the report, an engine performance analysis is presented where a model was used to simulate water injection in front of the LPC.

3.0 Performance Analysis

3.1 Performance Simulation Model

The PW4062A engine performance simulation model was modified for this study to incorporate the capability of injecting water either directly into the combustor or before the LPC. The performance levels of this simulation reflect a commercial off-the-shelf (COTS) PW4062A installed in the Boeing 747 nacelle and are consistent with a true thermodynamic representation of the pressures, temperatures, and airflow rates produced by this engine. This model assumes that water injected into the gaspath is totally evaporated at the point of injection. The injected water is in addition to normal humidity modeling. The normal modeling value is set at 60 percent relative humidity. Review of this modeling technique relative to measured engine data available for recent industrial gas turbine power system experimental testing verified that this is a realistic approach for water injected into the combustor. Table I provides a comparison of the model-predicted impact of water injection into the combustor fuel nozzles relative to measured data from an industrial Pratt & Whitney (P&W) FT8 gas turbine engine.

TABLE I.—WATER INJECTION TECHNIQUE COMPARISON OF FT8–1 MODEL WITH FT8–1 EXPERIMENTAL ENGINE DATA

Parameter[a]	Delta wet versus dry	
	Engine 421–2	FT8–1 model
ΔN_1, rpm	–22	–23
ΔN_2, rpm	–71	–71
ΔT_{25}, °R	–1.0	0.0
ΔT_3, °R	–2	0.0
$\Delta T_{4.9}$, °R	–43	–45
ΔLPC pressure ratio, percent	–0.20	0.00
Δoverall pressure ratio, percent	–.40	.20
ΔW_f, percent	2.50	2.40
ΔW_{2R}, percent	–1.20	–.50
ΔW_{25ILR}, percent	–1.40	–.77

[a]N_1 is low rotor speed.
N_2 is high rotor speed.
T_{25} is low-pressure compressor exit temperature.
T_3 is high-pressure compressor exit temperature.
$T_{4.9}$ is low-pressure turbine exit temperature.
LPC is low-pressure compressor.
W_f is fuel flow.
W_{2R} is low-pressure compressor inlet airflow.
W_{25ILR} is high-pressure compressor inlet airflow with instrumentation installed.

3.2 Predicted Impact of Water Injection on Engine Performance

Simulations were run for a number of takeoff conditions to evaluate the shift in parameter levels expected to result from water injection. While running these simulations, thrust was maintained constant for specific ambient temperature, mach number, and altitude conditions while the amount of water injected was varied from zero up to a water-to-fuel ratio equivalent to 1.5:1.

The predicted shifts in the high-pressure compressor exit temperature T_3, combustor exit temperature T_4, low rotor speed N_1, high rotor speed N_2, low-pressure turbine exit temperature $T_{4.9}$, burner pressure PB, fuel flow W_f, and engine pressure ratio EPR resulting from water injection directly into the combustor under sea-level static (SLS) standard day takeoff conditions are plotted as a function of water-to-fuel ratio in figures 1 and 2. The $T_{4.9}$ decreases linearly with increasing water-to-fuel ratio with a reduction of up to 65 °F occurring at a water-to-fuel ratio of 1.5:1, accompanied by a reduction in T_4 of up to 180 °F. with only a slight increase in T_3. The model also predicts a 0.75-percent drop in N_1 with a corresponding 0.28-percent drop in N_2 at a 1.5:1 water-to-fuel ratio.

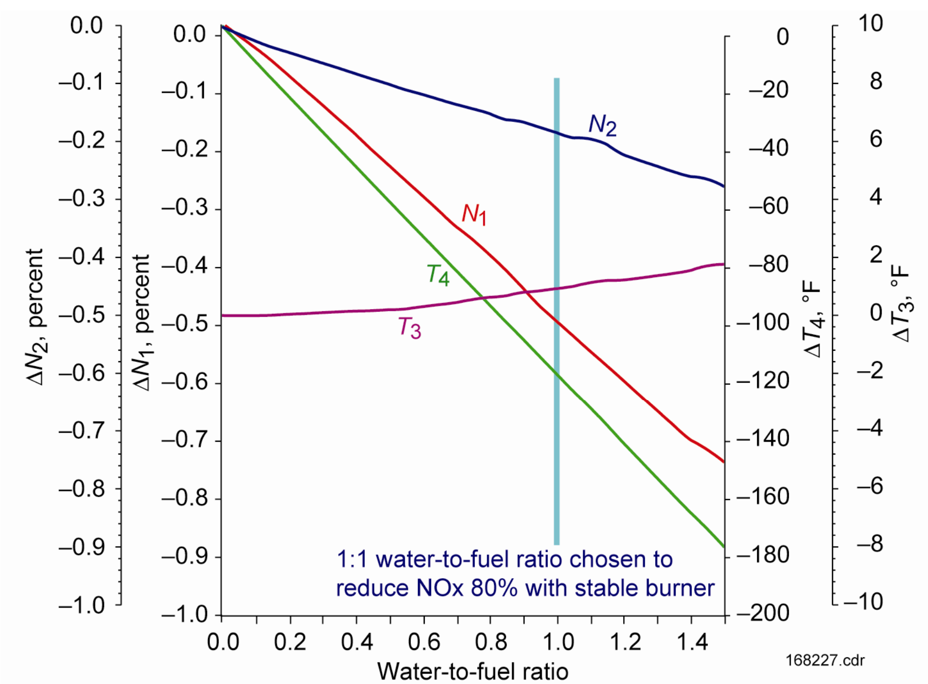


Figure 1.—Predicted impact of water injection directly into combustor of PW4062 aircraft engine at constant thrust: changes in high rotor speed N_2, low rotor speed N_1, high-pressure compressor exit temperature T_3, and combustor exit temperature T_4.

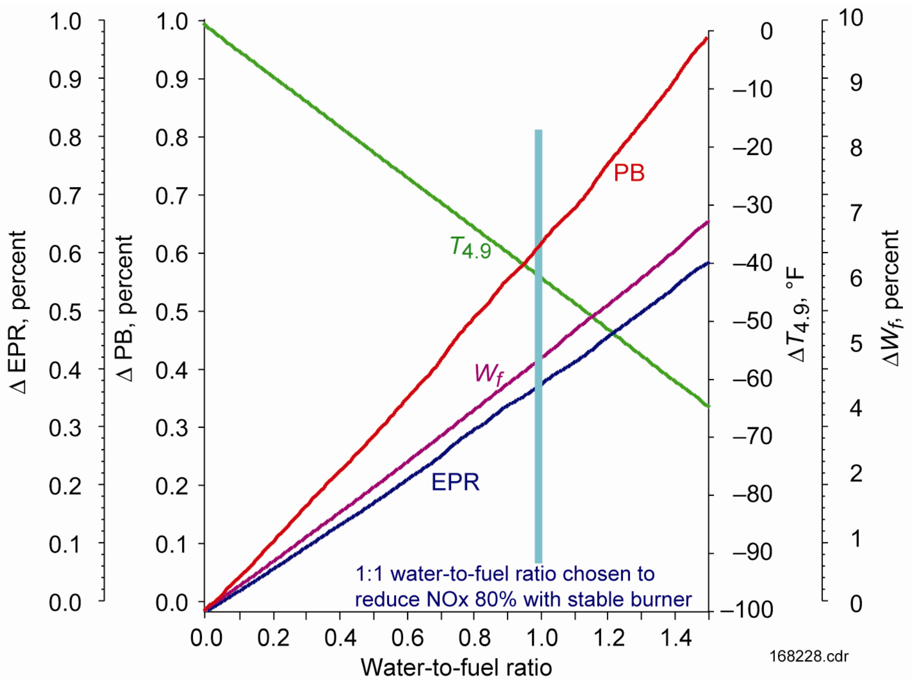


Figure 2.—Predicted impact of water injection directly into combustor of PW4062 aircraft engine at constant thrust: changes changes in engine pressure ratio (EPR), burner pressure (PB), fuel flow W_f, and low-pressure turbine exit temperature $T_{4.9}$.

3.3 Predicted Impact of Water Injection on LPC and HPC Operating Lines

The shift in LPC and HPC operating lines predicted to result from water injection directly into the combustor under SLS standard day conditions is plotted as a function of water-to-fuel ratio in figure 3. When water is injected directly into the combustor, the shift in the HPC operating line is expected to be a linear function of water-to-fuel ratio, with a 2.55-percent increase in HPC operating line occurring at a water-to-fuel ratio equal to 1.5.

4.0 Emissions and Analysis

Water injection has been successfully applied by P&W both to aeroengines, to help increment takeoff thrust, and to industrial aeroderivative engines, to decrease NO_x emission levels.

The P&W JT9D gas turbine engine injected water in the prediffuser, downstream of the exit guide vanes (EGVs) of the HPC but upstream of the combustor. The water completely vaporized before entering the combustor because of the high temperature of the compressed airstream. Water injected in this fashion entered the combustor both in the front end through the fuel nozzle and through the combustion holes and cooling passages. This method also had the added benefit of reducing the temperature of the air used to cool the turbine vanes.

For the P&W FT8 industrial aeroderivative engine, the water is mixed and emulsified with the fuel in a simple T-union, filter-screen arrangement in the fuel lines. Provisions are made to add the water upstream of the flow divider valve (FDV), as well as just before each fuel nozzle (fig. 4). An additional circuit can be added for steam injection. The resultant emulsion of water and fuel is quite uniform, as is needed for injection through the fuel nozzles into the combustor. In this arrangement, all the water is introduced into the front end of the combustor. The FT8 is normally operated at a 1.05:1 water-to-fuel mass ratio.

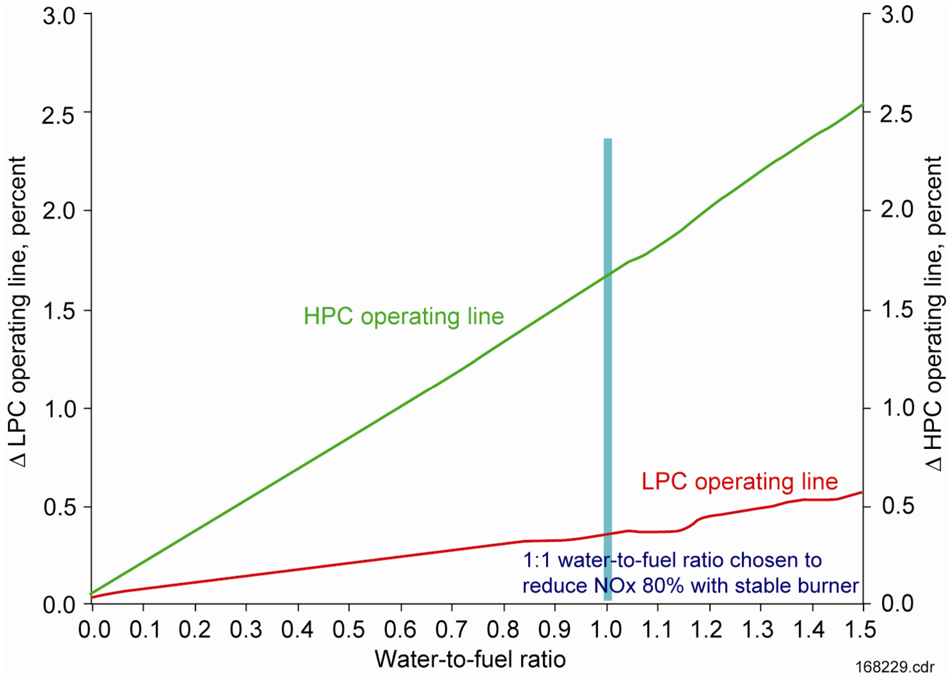


Figure 3.—Predicted impact of water injection directly into combustor of PW4062 aircraft engine at constant thrust: percent changes in low-pressure compressor (LPC) and high-pressure compressor (HPC) operating lines.

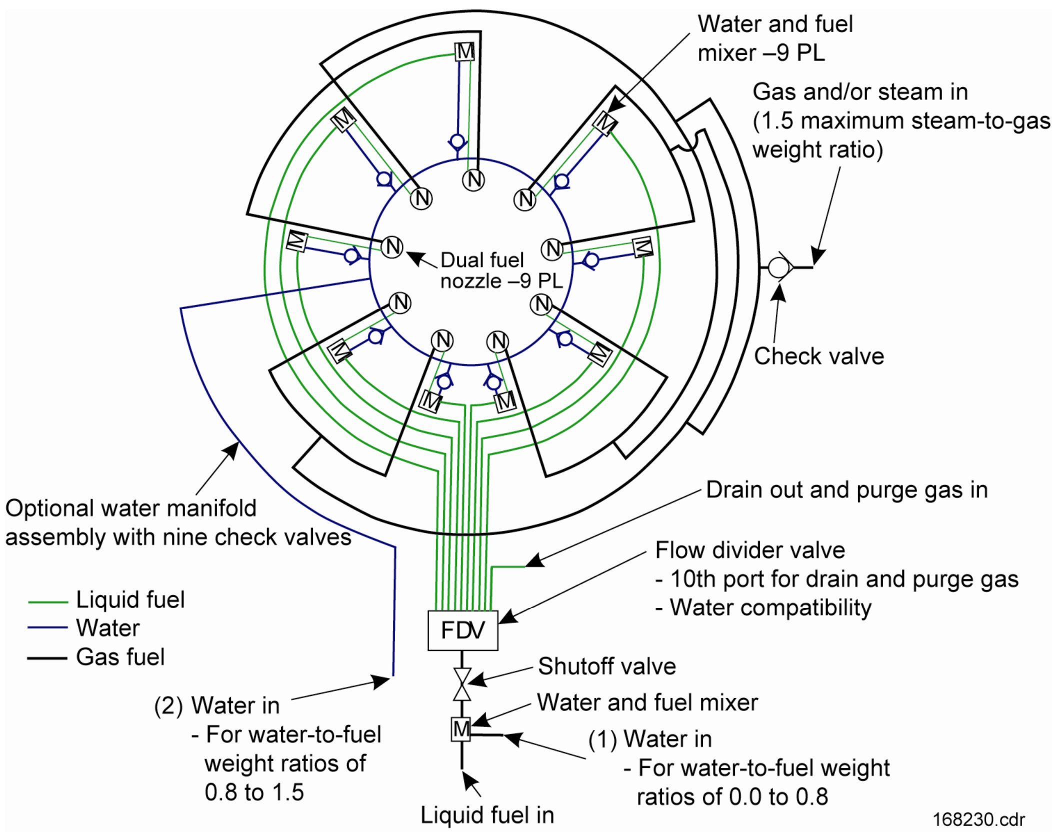


Figure 4.—Provisions made in FT8 gas turbine engine to inject water (1) before the FDV, (2) before the fuel nozzles, and (3) as a separate steam circuit.

Practical experience with the JT9D and the FT8 suggest that the stability limit of the proposed system for the PW4062 may be between 1.1:1 and 1.5:1 water-to-fuel mass ratio. Key indicators of reaching the stability limit would be a sharp increase in the amount of CO, followed by increased acoustic levels, then blowout. These stability limits are based on experience at steady-state operation; indeed, the FT8 is primarily run at steady-state conditions. Design for aeroengines requires that an acceptable stability margin exists to handle engine transients. Setting the water level at a 1:1 water-to-fuel mass ratio satisfies these requirements.

Applying commonly used corrections based on experiments that have been performed for various humidity levels, a water injection rate of 1:1 water-to-fuel would be expected to decrease the NO_x emissions index (EI; grams NO_x per kg fuel) 40 percent. These corrections are for constant fuel-air ratio and constant inlet temperature. The PW4062 cycle studies discussed above indicate that the fuel-air ratio is increased—as water is injected—to maintain constant thrust. From figure 1, it is seen that as the gas temperature entering the turbine decreases slightly more than 120 °F, the gas temperature entering the combustor remains basically the same. Given these impacts, the constant inlet temperature appears to be a good first approximation. Using the humidity correction factor as a basis for estimating water injection for NO_x reduction, a 40-percent reduction in takeoff EI NO_x translates to approximately a 30-percent reduction in NO_x Environmental Protection Agency parameter (EPAP).

Experience with the FT8 demonstrated an achieved NO_x reduction of about 85 percent for a 1:1 water-to-fuel ratio.[3] This would translate to an approximate 60-percent decrease in NO_x EPAP. It has been hypothesized that a large portion of the effect is due to the impact the water has on the flame shape and combustion length. Experience in other practical systems (e.g., industrial boilers) has shown that emulsified water-fuel mixtures appear to mix much more aggressively with the airstream, resulting in shorter flames. If these impacts are also true for gas turbines, then the formation time for NO_x in certain combustor geometries could be significantly reduced. However, in geometries such as the TALON family of combustors where reaction times have already been significantly reduced to lower NO_x, water addition has less impact on the overall NO_x levels, based on internal P&W studies.

The impact of water injection on the other emissions of interest—CO, unburned hydrocarbons (UHC), and smoke—is less defined. Water injection has been shown to increase or decrease these values depending on the execution of the water addition and the geometry of the combustor. For example, the FT8 had decreased smoke while the JT9D had increased smoke. CO levels typically increase as water injection levels are increased to the stability limits, but the 1:1 water-to-fuel ratio suggested here should not have an adverse impact. Unburned hydrocarbons tend to follow CO trends.

It is important to note that combustors are developed for operability, performance, cost, and durability, with NO_x and other emission levels being an added constraint. The inclusion of water as a requirement would trigger a significant combustor development program. Though probably not as extensive a development program as would be required for a new combustor, the development and validation for water injection would be similar in order of magnitude to the development of a new combustor; that is, it is more likely to be 50 to 75 percent of the cost than 10 percent of the cost. Given such a development program, a combustor with water injection would meet all applicable standards.

Given the significant cost of development for a combustor with water injection, the possible inclusion of a current-technology low-NO_x combustor system was considered. Since the PW4062, P&W has made significant progress in NO_x reduction technology. The TALON X combustor technology, being developed with NASA funding, is capable of meeting all current and proposed standards, as well as exceeding all customer-driven engine study requirements. Projections for a PW4062 cycle indicate NO_x reduction levels of 35 to 40 percent in the range of water injection levels studied. Further, the inclusion of this combustor would not require any significant modifications to controls or fuel systems, nor would it require any additional airport support, water supply, or aircraft modifications.

[3]Fox, T.G.; and Schlein, B.C.: Full Annular Development of the FT8 Gas Turbine Combustor. J. Eng. Gas Turbines Power, vol. 114, 1992, pp. 27–32.

Note that the impact of water injection on the next-generation low-NO_x aeroengine combustors is not defined. P&W has experience with both lean-direct-injection (LDI) low-NO_x combustors and high-intensity combustion systems such as the TALON X. The LDI systems studied at P&W operate near the lean stability limits to decrease NO_x. Adding moisture would reduce flame temperatures and bring the combustion process even closer to the stability limit. To maintain operability, more fuel would likely be required at some operating points. To implement water misting, the system would have to be carefully designed to be able to accommodate both wet and dry operation. This might significantly compromise the NO_x benefits in aeroengine applications. The impact of adding water to a high-intensity combustion system such as the TALON X is even less clear. Aggressive mixing and short reaction times achieve much of the NO_x reduction in this approach. Adding water may interfere with the designed balance between kinetics and aerodynamics. Some NO_x reduction is expected from the impact of increased humidity, but the degree of reduction has not yet been established since the burner would need to be designed for both wet and dry operation similar to the LDI approach. P&W has conducted preliminary tests of injecting water into a TALON III combustor and did not see the level of reduction that has been reported by others (see footnote 1).

In summary, the projected reduction in NO_x due to water addition at a 1:1 ratio is likely to be between 30 and 60 percent in EPAP for the PW4062 combustor and would require a significant development program. The insertion of a TALON X combustor in the PW4062 is expected to reduce NO_x by 35 to 40 percent. Finally, the impact of water injection on next-generation low-NO_x combustors is uncertain and may be much less than the impact on current combustors.

5.0 Performance Impact of Water Injection at Maximum Recommended Water-to-Fuel Ratio

For a water-to-fuel ratio of 1:1, which represents the maximum recommended water-to-fuel ratio from a standpoint of combustor stability, the predicted shifts in engine performance parameter values resulting from water injection directly into the combustor under SLS standard day takeoff conditions are summarized in table II. Key performance impacts are the reduction of 120 °F in combustor exit temperature, the EPR shift at constant thrust, and negligible change in rotor speeds. As the engine thrust is controlled by EPR, this thrust-EPR shift drives a need to modify the electronic control system to be able to recognize when water injection is being used and to adjust the rating structure as required to ensure certified thrust levels are obtained during takeoff.

Using water injection directly into the combustor with a water-to-fuel ratio equal to 1:1, the model predicts a 1.6-percent increase in HPC operating line accompanied by a 0.4-percent increase in LPC operating line to occur under SLS standard day takeoff conditions. Generally, stability-neutral engineering changes are requirements, with negative impacts being an exception (especially in regards to takeoff flight regime). As a result, the turbine durability assessment is based on a rematch configuration (between compressor and turbine) to preserve a stability-neutral design (the rematch impact is discussed in sections 9.0 and 9.1).

TABLE II.—EFFECT OF WATER INJECTION AT 1:1 WATER-TO-FUEL RATIO ON PW4062 AIRCRAFT ENGINE PERFORMANCE
[Sea-level static 60 000 lb_f takeoff thrust.]

Change in parameters[a]	
ΔTSFC, percent	4.3
ΔTSFC at 51 000 ft, percent	0.0
Δthrust, percent	0.0
Change in rotor speeds	
ΔN_1, low rotor, percent	–0.5
ΔN_2, high rotor, percent	–.2
Change in temperatures[b]	
ΔEGT, exhaust gas, °F (°C)	–43 (–24)
ΔT_{125}, fan exit, °F	–1
ΔT_{25}, LPC exit, °F	–2
ΔT_3, HPC exit, °F	1
ΔT_4, combustor exit, °F	–120
ΔT_{45}, HPT exit, °F	–66
Change in pressures[c]	
Δfan exit, P_{125}, percent	–0.2
ΔLPC exit, P_{25}, percent	–.4
ΔHPC exit, P_3, percent	.6
ΔP_4, Combustor exit, percent	.7
ΔP_{45}, HPT exit, percent	.5
ΔEPR, percent	.4
Change in airflows[b]	
$\Delta W2AR$, fan inlet, percent	–0.3
ΔW_{2R}, LPC inlet, percent	–.6
$\Delta W_{2.5R}$, HPC inlet, percent	–.3
Change in fuel flow	
ΔW_f, fuel flow, percent	4.3
Change in operating lines[b]	
Δfan, percent	0.0
ΔLPC, percent	.4
ΔHPC, percent	1.6

[a]TSFC is thrust-specific fuel consumption.
[b]EGT is exhaust gas temperature.
LPC is low-pressure condenser.
HPC is high-pressure condenser.
HPT is high-pressure turbine.
[c]EPR is engine pressure ratio.

6.0 Hot-Section Life Improvement

The turbine hot-section life (airfoil durability) assessment starts with the evaluation of the impact that water injection has on the performance of the high-pressure turbine (HPT) blade. A series of proprietary temperature adders based on fleet experience are used in conjunction with the original performance parameters to determine the basis for the airfoil durability assessment. These adders include performance-miss factors, engine-to-engine variation, speed power setting, transient overshoot, and deterioration. In addition to these elements, other design elements, such as pattern factors, profile factors, performance-to-gas temperature ratios, relative-to-absolute temperature ratios, coolant-to-compressor discharge temperature ratios, and overall film and cooling effectiveness with and without thermal barrier coatings (TBCs), are included in the durability analysis. The water injection case considers a 1:1 water-to-fuel ratio in the combustor.

Table III provides the results for the durability analysis of the HPT blade in terms of the difference between the engine with water injection and the engine without water injection. T_{abs}, T_{rel}, $T_{rel, pk}$, $T_{c, supply}$, and N_2 denote the absolute temperature, the relative temperature, the peak relative temperature, the blade supply coolant temperature, and the HPT rotor speed, respectively. The results presented in this table show that the relative peak gas temperature decreases by 147 °F. Consequently, this provides an airfoil metal temperature reduction of 78 °F. Using inhouse life assessment tools for TBC spallation and metallic and alloy oxidation, an expected life improvement of 1.29 times is noted for the blade operating in a water injection environment.

TABLE III.—PERFORMANCE PARAMETER DELTAS FOR DURABILITY ASSESSMENT OF PW4062 AIRCRAFT ENGINE—DELTA FROM ENGINE WITH NO WATER INJECTION

Rating	Change in parameters				
	Maximum gas total temperature, ΔT_{abs}, °F	Relative gas static temperature, ΔT_{rel}, °F	Peak relative gas temperature, $\Delta T_{rel, pk}$, °F	Coolant supply temperature, $\Delta T_{c, supply}$, °F	High rotor speed, ΔN_2, rpm
Takeoff	–131.5	–125.1	–147.3	–7.2	–25.0
Climb	1.9	1.8	3.0	–4.9	1.0
Cruise	1.9	1.8	2.8	–3.6	3.0
Descent	1.7	1.6	2.1	–.7	–173.0
Thrust reversal	4.8	4.6	5.9	–2.8	7.0

7.0 Maintenance Cost Improvement

In this section maintenance costs associated with water injection systems are examined.

7.1 Background

Water injection has been proposed as a means to significantly reduce engine NO_x emissions in aircraft engines. Water injection is a well-known method of reducing emissions and has been used extensively in industrial engines, but it has not been used for that purpose in aircraft engines. Water injection was used in the early 1970s on the JT9D–3 engine for takeoff thrust augmentation. While this was successful in boosting takeoff thrust, a number of maintenance issues were associated with the use of water injection in that application. High on the list of challenges was the need to use demineralized water. This was a significant challenge, because use of contaminated water caused turbine airfoil corrosion and sulfidation and led to very low time on wing. If contaminated water were used, it would have a dramatic adverse impact on on-wing time and maintenance cost.

If a water injection system were installed in an aircraft, a separate storage tank would be required to store the water, along with a water pump, valves, lines, and switches. These parts would require additional maintenance resources, but they are assumed to be part of the aircraft system and are therefore not included in the delta maintenance cost presented here for the engine. The impact of any possible changes to the engine fuel nozzles and manifold are also ignored for the purposes of this study.

All the water in the tank is assumed to be consumed during takeoff, so the water tank would need to be serviced after every flight leg, just like fuel. This would require storage of demineralized water at each line station, a big logistical challenge for the airlines. If a system were designed not to use all of the water at takeoff (i.e., designed to tanker water as fuel is sometimes tankered between line stations), then there could be a concern with the water in the tank freezing at altitude. Again, the impact of these concerns is not included in the engine maintenance cost presented here.

While water injection in the JT9D was used for thrust augmentation, the current proposal is to maintain the current takeoff thrust level and use water injected directly into the combustor to reduce emissions. This would also result in a significant decrease in combustor exit gas path temperatures that should increase turbine airfoil life, increase on-wing time, and reduce engine maintenance cost.

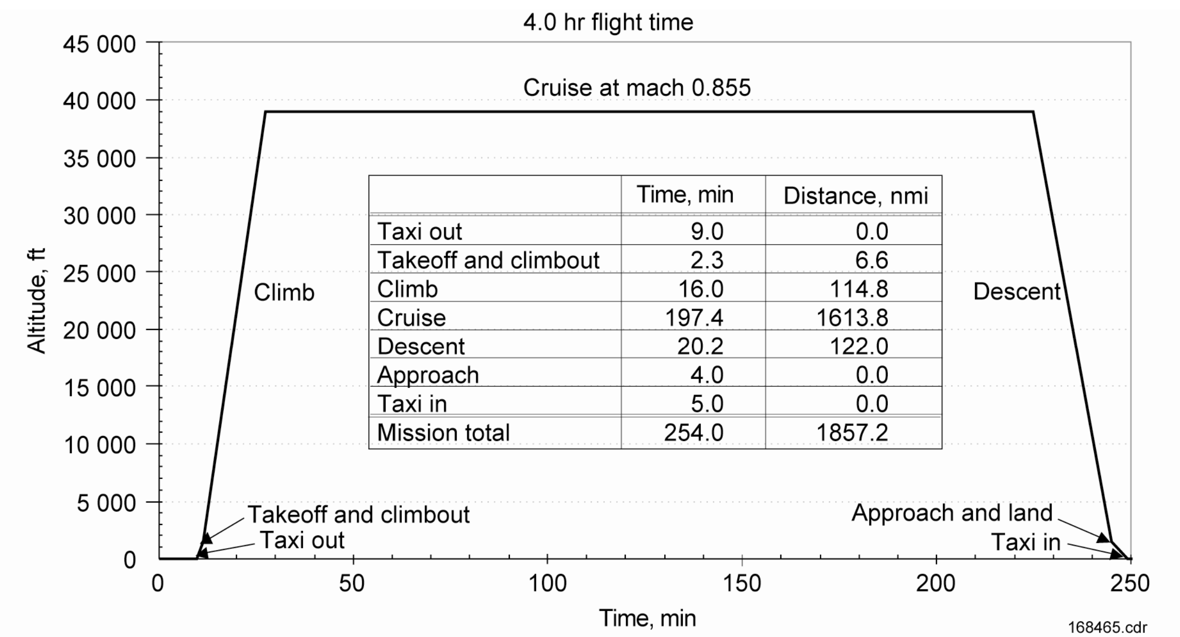
In assessing absolute maintenance cost for the engine as a whole, however, there are additional and highly significant factors, either not in the scope of this analysis and/or not under the control of engine manufacturers. Consideration of these additional factors is critical before any final decision to incorporate water injection systems is made.

First is the significant opportunity for contaminants to get introduced to the engine through service, distribution, or storage problems or through errors by service personnel. Efforts to calculate the likelihood of this impact are properly executed by operators. Historical experience with such systems, while dated, could provide a start for such a study. Given the very significant potential outcome of this issue alone, maintenance cost results reached here could clearly be diminished or even turned to a negative outcome. There is also a distinct possibility that unscheduled engine removal (UER) rates could be adversely impacted.

Second, the benefits resulting from turbine temperature alone may not be realized, as other maintenance thresholds may be exceeded leading to the replacement of turbine blades at an interval significantly less than the potential recognized in the study. For example, if the injection of water increases the probability of corrosion in parts other than the turbine airfoils, maintenance intervals could be set earlier than the newly improved turbine airfoil replacement would require. Lacking the execution of a complete system design study, it is not likely that this assessment could be established with any fidelity. Historical data on water injection from an earlier fleet (e.g., JT9D-powered Boeing 747s) when maintenance intervals were significantly shorter than today’s would likely not be applicable.

7.2 Results

The PW4062 engine on the Boeing 747, on a 4.0-hour flight with 10 percent takeoff derate, is used as the basis for determining maintenance cost improvement (fig. 5). Excluding the effects of life-limited parts, about 65 percent of the maintenance cost is for scrapped material, while the remaining 35 percent is for labor and repair. This assumes maintenance in a full-service airline shop at a labor rate of $75 per labor hour.



	Time, min	Distance, nmi
Taxi out	9.0	0.0
Takeoff and climbout	2.3	6.6
Climb	16.0	114.8
Cruise	197.4	1613.8
Descent	20.2	122.0
Approach	4.0	0.0
Taxi in	5.0	0.0
Mission total	254.0	1857.2

Figure 5.—Flight profile of Boeing 747–400 aircraft with PW4062A engine used for maintenance cost evaluation.

Water injection should reduce combustor exit temperature at takeoff thrust by 120 °F according to the P&W Performance Group (sec. 3.0). The P&W Turbine Durability Group analysis indicates this would result in an airfoil life improvement of at least 29 percent (sec. 6.0). The improved turbine airfoil life should then result in a 16-percent reduction in shop visit rate (SVR) and a $22 per EFH decrease in engine maintenance cost. Again, this is strictly the result obtained from an estimation process that only considers the effect on airfoil durability of a reduction in turbine gas temperature. Other factors, as discussed in section 7.1, are capable of reducing the benefit and possibly even resulting in a net increase in maintenance cost.

8.0 Overview of Water Distribution and Injection System

A schematic of the FT8 water injection system with three different possible injection circuits is shown in figure 4. The possible points for injection are before the FDV, before each fuel nozzle, and as a separate injection circuit, which for the FT8 is shown as a steam injection circuit. Other points for water injection, such as in the prediffuser or elsewhere in the combustor, were considered but rejected as requiring additional diffuser case penetrations and contributing to further uncertainties in operation. Indeed, the largest impacts of water injection appear to occur when the water-fuel emulsion is injected from the fuel nozzle.

For the study application for a PW4062, it is not envisioned that all three circuits would be needed. The preferred method is injection upstream of the FDV, which carries with it a minimum of hardware, control requirements, and cost. However, the volumes and fill rates of the manifolds feeding from the FDV to the nozzles may become too large in this embodiment. In effect, a water-to-fuel ratio of 1:1 would require cross-sectional areas a little less than twice the size of the current fuel-only embodiment. This would lead to longer fill times on lightoff and larger volumes of fuel being released on shutdown. These impacts may not be acceptable. Thus, the second method would be the injection and mixing of water just before the fuel nozzles. This would require a separate manifold for the water, designed and demonstrated to provide equal amounts of water to each fuel nozzle. This would eliminate the concern with increased fuel manifold volumes, while retaining the current fuel nozzles, modified only to accept the higher flows at high power.

Note that the behavior of the fuel nozzles is a key design concern in combustor development. The sizes of the various passages are chosen to minimize potential for coking. The spray characteristics are directly dependent on the area of the jets. The size of these jets and fuel passages determine the flow number of the fuel nozzle, which must match the pressure available from the fuel pump. Sizing the fuel nozzle for twice the mass flow would increase the passage area and jet size, increasing coking potential at cutback, cruise, and descent, as well as decreasing spray effectiveness at lightoff and lean blowout conditions.

Two approaches can be used to reduce these impacts. The first and preferred approach would be to significantly increase fuel pressure when water injection is turned on. In theory, the water-fuel mixture could be forced through passages sized for fuel alone by increasing the pressure enough. However, probable practice would resize the fuel nozzles minimally—within the design and production envelope—while increasing pump capability moderately. The second approach would be to design the fuel nozzles to inject the water at the tip, perhaps not even emulsifying the water-fuel mixture. This minimizes fuel system impacts, but makes nozzle design more complex and heavier and can make combustor design and operation more problematic.

In summary, the preferred approaches are, in order:

(1) Mix the water before the FDV, replacing the pump and control logic to increase fuel delivery pressure when water injection is required and increasing the cross-sectional area of the manifold and fuel nozzle passages and jet orifices in a moderate fashion.

(2) Mix the water before each fuel nozzle, replacing the pump and control logic to increase fuel delivery pressure when water injection is required and increasing the cross-sectional area of the fuel nozzle passages and orifices in a moderate fashion.

The overall weight impact of either option of the water injection system is estimated to be roughly 70 lb per engine as shown in table IV.

TABLE IV.—EFFECT OF WATER INJECTION SYSTEM AND PROBABLE CHANGES IN FUEL SYSTEM ON WEIGHT OF PW4062 AIRCRAFT ENGINE

Name[a]	Option 1,[b] lb	Option 2,[c] lb
Changes from water system component weights		
Water pump	(assumed to be part of aircraft system)	
Water metering unit	20.3	20.3
Tube from FMU to FDV	.4	.4
Water flowmeter	3.5	3.5
Flow distribution valve	----	3.8
Manifold and extensions	----	9.3
Flowmeter support	1.2	1.2
WMU support	.2	.2
Water manifold brackets	10.5	10.5
Water/fuel mixers	.3	3.0
Subtotal for water system	36.4	52.2
Probable changes from fuel system weights		
Fuel pump	20.0	20.0
Fuel metering unit	5.0	0.0
Tube from FMU to FDV	.1	0.0
Fuel flowmeter	1.0	0.0
Flow distribution valve	1.0	1.0
Manifold and extensions	2.5	0.0
Fuel nozzles	0.0	0.0
Subtotal for fuel system	29.6	21.0
Total for options	**66.0**	**73.2**

[a]FMU is flow metering unit.
FDV is flow divider valve.
WMU is water metering unit.
[b]Water is mixed before the flow divider valve.
[c]Water is mixed before each fuel nozzle.

Water injection system components were assumed to be roughly the same size and weight as the fuel system components, given the similarity of the flow rates. The fuel recycle loop was not included; it was assumed that the water would be a single-pass system. It was also assumed that the fuel nozzles, though specific for the proposed system, would be approximately the same weight for options 1 and 2 above as they are now. The pump for the water system is expected to be part of the aircraft system, and therefore is not included in the engine system weight. The water metering unit, analogous to the fuel metering unit, is considered part of the engine system, as it will be directly controlled by the engine control system.

The weight of the fuel pump was estimated to be increased to account for the increased pressures that the system would likely demand: Table IV only shows the increase. Similar increments are shown for the other components of the fuel system likely to be impacted by the increased volumetric flow rates and pressures of option 1. Option 2 impacts fewer components. There would have to be some tailoring done in the flow metering unit, and the flowmeter and FDV are likely to be somewhat impacted by the increased pressure; however, the delivery manifold and tubes will probably not need to be resized.

The price of a water injection retrofit kit is estimated at approximately $375,000 per engine (about 3 percent of the engine list cost), again, based on the similarity of the parts to those of the fuel system. This is assuming that the kit will be installed concurrently with a major engine overhaul that will include turbine airfoil replacement so the rematch (see sec. 9.0) can be included at no extra cost.

As an option to a new engine at production, the package price will be lower because the fuel nozzles will not have to be replaced. The anticipated list price for this option is estimated at $250,000 per engine. The actual price for an option on a new engine is likely to be very much lower due to the normal competitive marketing situation for new engine sales.

9.0 HPC Operating Line Mitigation

A design change to the HPT and LPT would provide the ability to restore both the LPC and HPC stability margin loss resulting from the use of water injection during takeoff. The model indicates that a rematch consisting of a 1.5-percent increase in HPT inlet area and a 0.8-percent increase in LPT inlet area would be required to restore nominal stability margin under SLS standard day takeoff conditions when injecting water directly into the combustor.

9.1 Performance Impact of Turbine Rematch

The impact on engine performance during takeoff, climb, and cruise associated with incorporating the turbine rematch needed to restore bill-of-material (BOM) HPC surge margin is summarized in table V. The most significant penalty associated with incorporating the turbine rematch is the increase in cruise thrust-specific fuel consumption (TSFC) of approximately 0.4 percent. For the Boeing 747–400ER aircraft equipped with PW4062A engines, the impact of incorporating water injection with the rematched turbine corresponds to approximately 543 lb (81.1 gal) of extra fuel burned on a typical 3000 nmi flight.

The takeoff performance impact for water injection plus rematched turbine is plotted in figures 6 through 9. The flight profile (equivalent power setting) is plotted in figures 10 through 12.

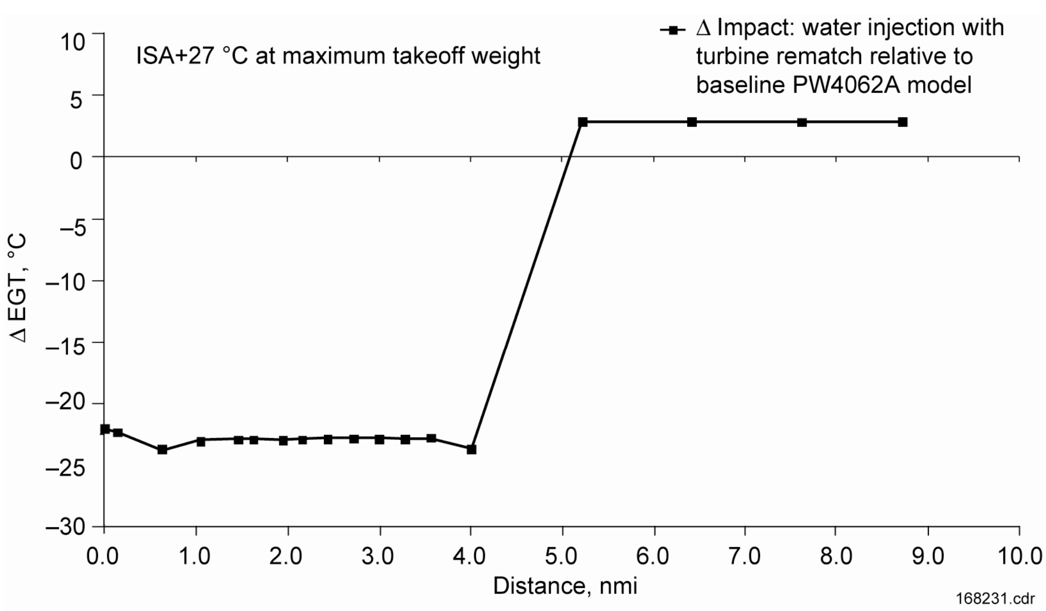


Figure 6.—Impact of water injection with turbine rematch on takeoff exhaust gas temperature (EGT) of PW4062A aircraft engine.

TABLE V.—EFFECT OF TURBINE REMATCH ON PW4062 AIRCRAFT ENGINE PERFORMANCE

	Sea-level static 60 000 lb_f takeoff thrust	35 000 ft at 0.8 mach cruise bucket thrust = 8000 lb	35 000 ft at 0.8 mach maximum climb EPR[a]
Change in parameters[b]			
ΔTSFC	4.8	0.4	0.3
ΔTSFC at 31 000 ft, percent	.6		
Δthrust, percent	0.0	0.0	–.1
Change in rotor speeds[c]			
ΔN_1, percent	–0.6	–0.1	–0.2
ΔN_2, percent	0.0	.1	.1
Change in temperatures[d]			
ΔEGT, °F (°C)	–35 (–19)	6	6
ΔT_{125}, °F	–1	0	0
ΔT_{25}, °F	–3	–1	–1
ΔT_3, °F	–3	–5	–6
ΔT_4, °F	–116	0	0
ΔT_{45}, °F	–60	3	4
Change in pressures[e]			
ΔP_{125}, percent	–0.3	–0.1	–0.1
ΔP_{25}, percent	–.9	–.5	–.5
ΔP_3, percent	–.8	–1.4	–1.6
ΔP_4, percent	–.8	–1.4	–1.6
ΔP_{45}, percent	–.3	–.9	–.9
ΔEPR, percent	.5	.2	.0
Change in airflows[f]			
$\Delta W2AR$, percent	–0.4	–0.1	–0.1
ΔW_{2R}, percent	–.7	.0	–.2
$\Delta W_{2.5R}$, percent	0.0	.4	.2
Change in fuel flow[g]			
ΔW_f, percent	4.8	.4	.4
Change in operating lines[h]			
Δfan, percent	0.0	0.0	0.0
ΔLPC, percent	0.0	–.5	–.5
ΔHPC, percent	0.0	0.0	0.0

[a]EPR is engine pressure ratio.
[b]TSFC is thrust-specific fuel consumption.
[c]N_1 is low rotor speed.
N_2 is high rotor speed.
[d]EGT is exhaust gas temperature.
T_{125} is fan exit temperature.
T_{25} is low-pressure compressor exit temperature.
T_3 is high-pressure compressor exit temperature.
T_4 is combustor exit temperature.
T_{45} is high-pressure turbine exit temperature.
[e]P_{125} is fan exit pressure.
P_{25} is low-pressure compressor exit pressure.
P_3 is high-pressure compressor exit pressure.
P_4 is combustor exit pressure.
P_{45} is high-pressure turbine exit pressure.
EPR is engine pressure ratio.
[f]$W2AR$ is fan inlet airflow.
W_{2R} is low-pressure compressor inlet airflow.
$W_{2.5R}$ is high-pressure compressor inlet airflow.
[g]W_f is fuel flow.
[h]LPC is low-pressure compressor.
HPC is high-pressure compressor.

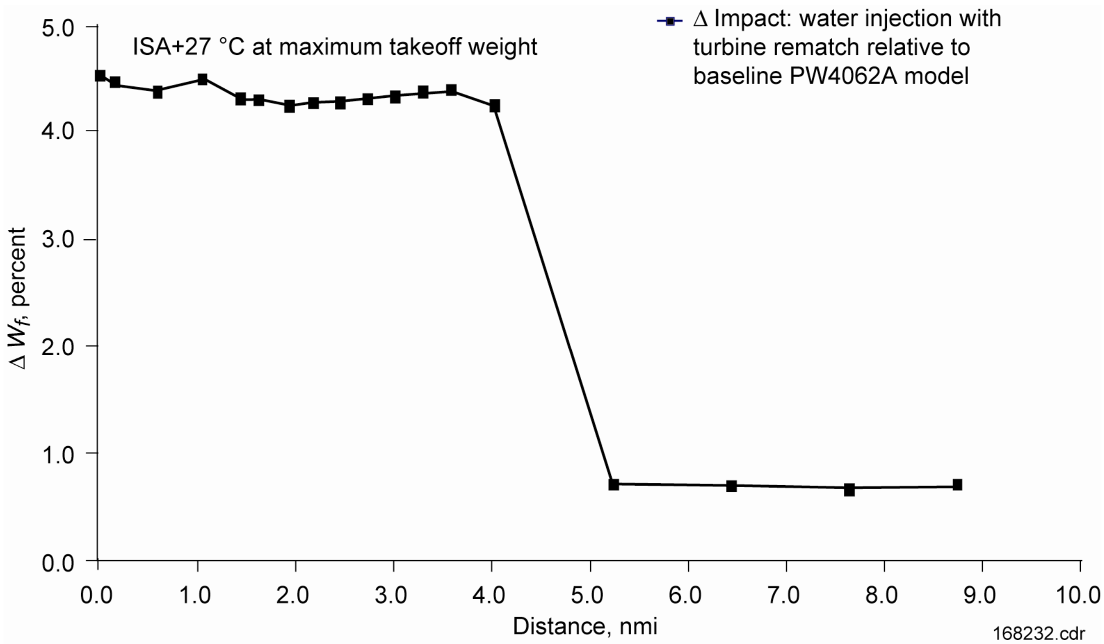


Figure 7.—Impact of water injection with turbine rematch on fuel flow W_f of PW4062A aircraft engine.

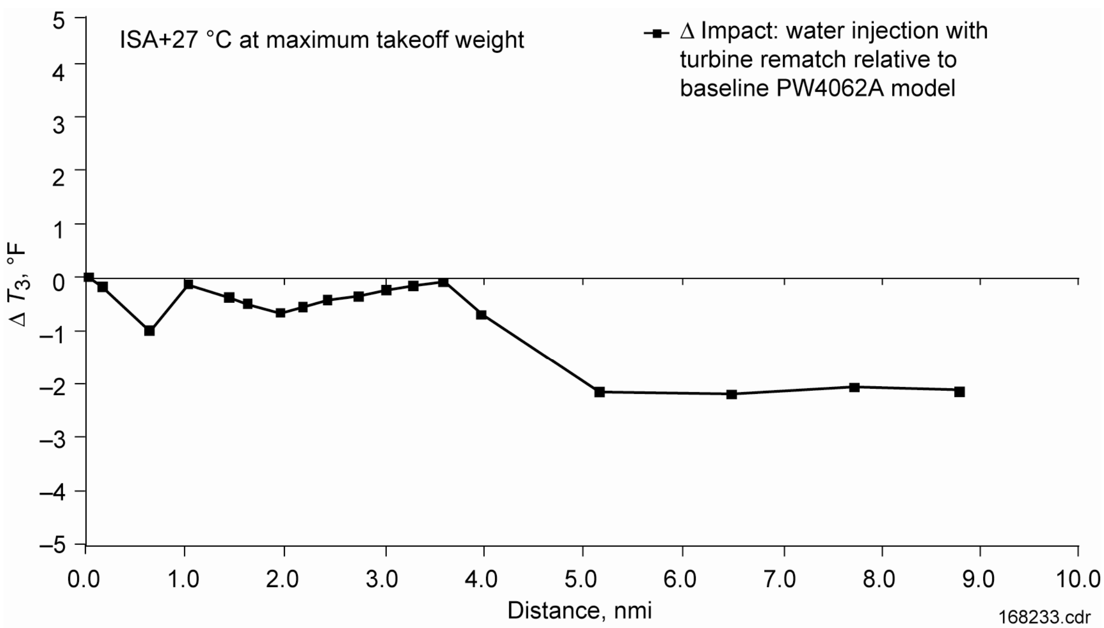


Figure 8.—Impact of water injection with turbine rematch on takeoff high-pressure compressor exit temperature T_3 of PW4062A aircraft engine.

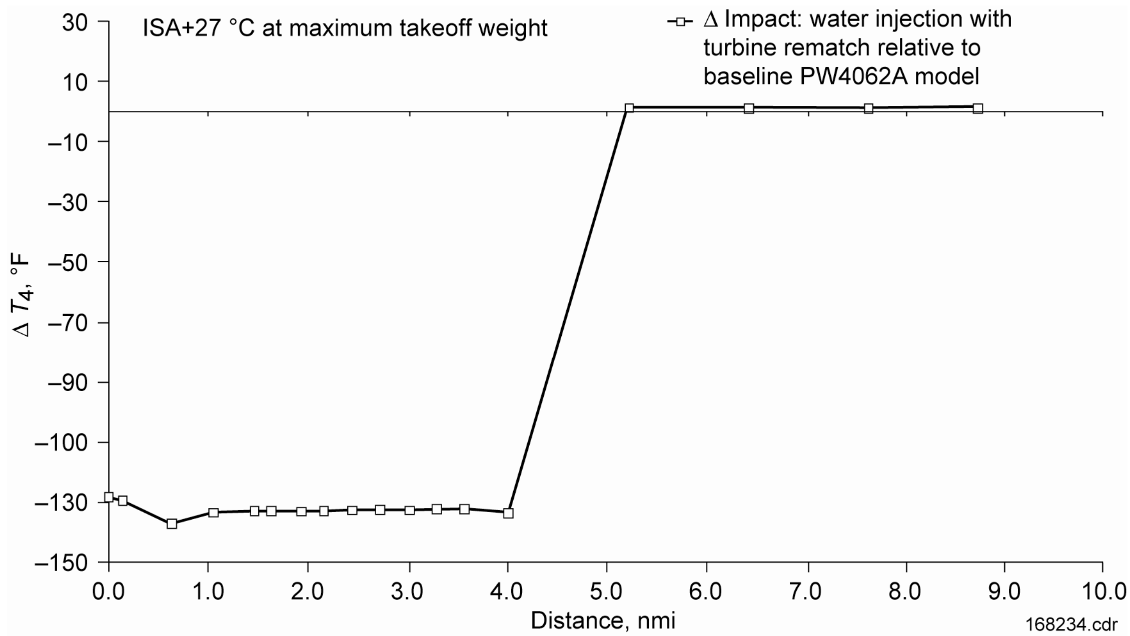


Figure 9.—Impact of water injection with turbine rematch on takeoff combustor exit temperature T_4 of PW4062A aircraft engine.

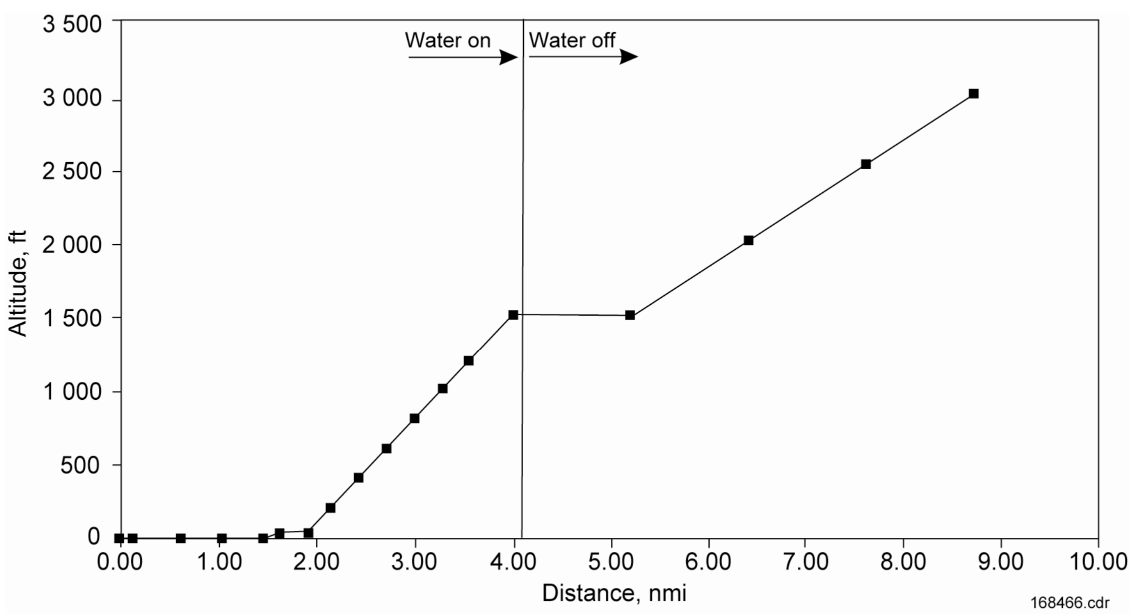


Figure 10.—Impact of water injection with turbine rematch on altitude versus distance flight profile for Boeing 747–400ER aircraft with PW4062A engine.

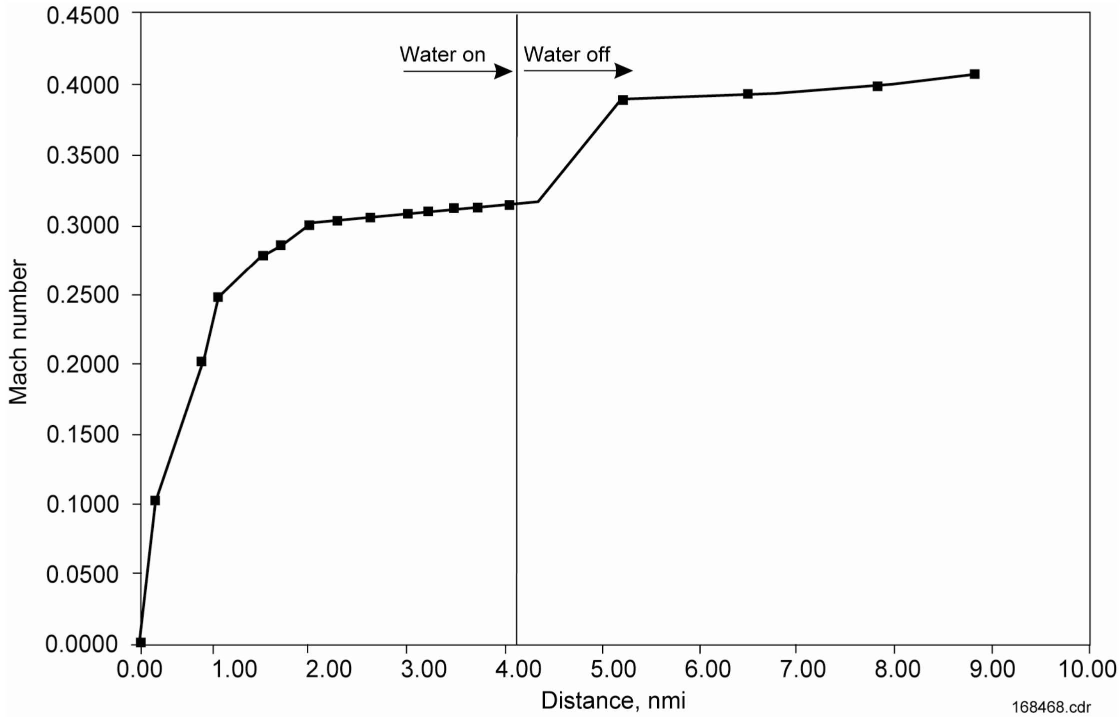


Figure 11.—Impact of water injection with turbine rematch on mach number versus distance flight profile for Boeing 747–400ER aircraft with PW4062A engine.

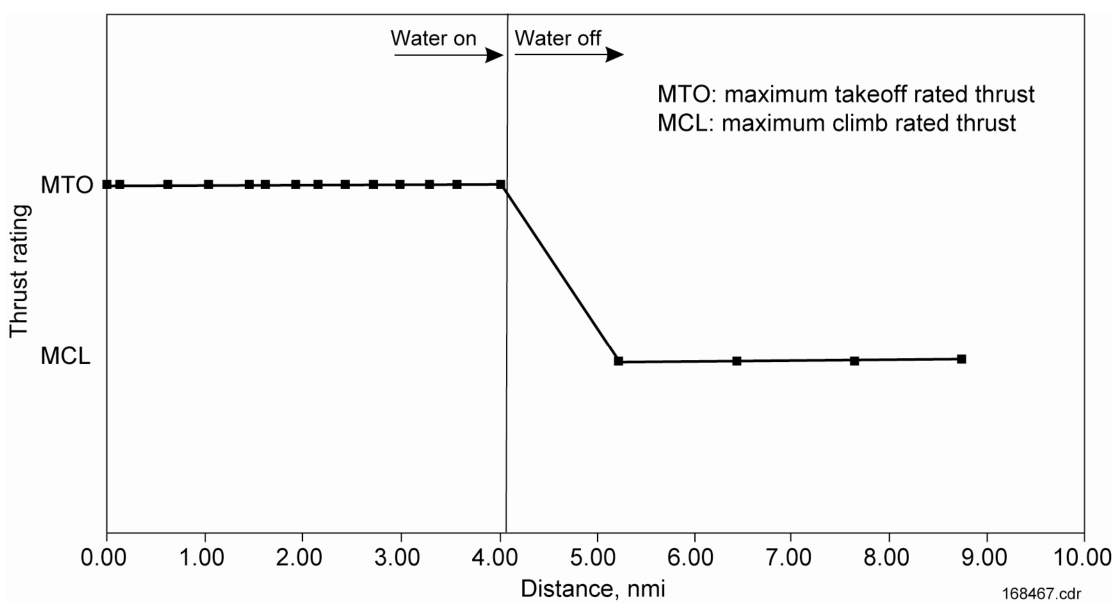


Figure 12.—Impact of water injection with turbine rematch on thrust rating versus distance flight profile for Boeing 747–400ER aircraft with PW4062A engine.

10.0 System-Level Impacts

As discussed in section 5.0, the thrust-EPR shift that occurs with water injection drives a need to modify the electronic control system to be able to recognize when water injection is being used and to adjust the rating structure as required to ensure certified thrust levels are obtained during takeoff. PW4062 engine systems that would need further study before a water injection system could be incorporated include

(1) Electronic engine control modifications (input for water injection)
(2) Compressor stability assessment (review of stability audits—turbine rematch)
(3) Secondary flow—turbine cooling air assessment
(4) Secondary flow—thrust balance assessment
(5) Thermal clearance control system supply pressure evaluation
(6) Combustor pattern factor assessment (engine test)
(7) Combustor CO, hydrocarbon (HC), and smoke evaluation (engine test)
(8) Engine/aircraft noise assessment
(9) Environmental control system supply pressures (if turbine rematch required)

Expected engine certification testing that would be required to verify acceptability of water injection (following water injection development testing) would include

(1) Sea-Level Experimental Part 33 Engine Test
- Performance evaluation
- Control logic development/functional verification
- Combustor exit pattern factor evaluation
- Combustor emissions/smoke evaluation
- Combustor operability evaluation (blowout)

(2) FAR 33.65, “Surge and stall characteristics” (stability evaluation)
Start Stall Margin Testing (if fuel nozzle modification is required)
(3) FAR 33.73, “Power or thrust response” (thrust response evaluation)
(4) FAR 33.89, “Operation test”
(5) Sea-Level 150-Hour Endurance Part 33 Test
(6) Boeing 747 Part 25 Certification

The cost of the aforementioned analyses, engine tests, and documentation is estimated at $50 million and will be recouped in the price of retrofit kits or in newly manufactured PW4062 engines sold with these parts included as options. If a completely new engine were created with a water injection system as an integral or optional part, the additional cost would be much lower, possibly $10 million, as the validation and certification testing would be conducted concurrently with the typical engine development process. The recovery of these nonrecurring costs is included in the retrofit or option kit price described in section 8.0.

11.0 Noise Suppression From Water Injection

A study was conducted for the PW4062 to investigate the acoustic impact of water injection into the combustor, including the required turbine area rematch. The study was conducted for the 747–400ER at 910 000 lb takeoff gross weight (TOGW) and 666 000 lb landing weight (LDW) for the three acoustic conditions of sideline, cutback, and approach. Required inflight-corrected thrust levels were obtained from Boeing for the subject aircraft and thrust rating.

The inflight engine performance was studied to compare the fan corrected speed (NLR2A) and mass-averaged jet velocity (MAVEL) at the required inflight net corrected thrust for the three acoustic flight conditions. These two parameters are used to correlate fan and jet noise.

The results are summarized below:

(1) Sideline—The turbine rematch alone had no impact on the predicted MAVEL and reduced the required corrected fan speed at the required inflight net thrust level.

Water injection combined with the required turbine rematch reduced the required fan speed and expected jet velocity at the required inflight net thrust requirement. Based on this, the proposed changes are predicted to slightly reduce (<0.3 EPNdB) the present certified sideline noise levels of the 747–400ER/PW4062A aircraft at 910 000 lb TOGW and 666 000 lb LDW. Figures 13 and 14 show this effect is relatively insensitive to thrust level, so this benefit is expected to be consistent over a range of aircraft TOGW.

(2) Cutback—The turbine rematch alone had no impact on the predicted MAVEL and slightly reduced (2 rpm) the required NLR2A at the required inflight net thrust level.

Water injection combined with the required turbine rematch reduced the required fan speed and expected jet velocity at the required inflight net thrust requirement as shown in figures 15 and 16. Based on this, the proposed changes are predicted to slightly reduce (~ 0.1 EPNdB) the present certified sideline noise levels of the 747–400ER/PW4062A aircraft at 910 000 lb TOGW and 666 000 lb LDW. This effect is relatively insensitive to thrust level, so this benefit is expected to be consistent over a range of aircraft TOGW.

(3) Approach—The required fan speed and jet velocities, at constant thrust, were unchanged by the turbine rematch, and water injection is not used at approach. No noise impact is expected.

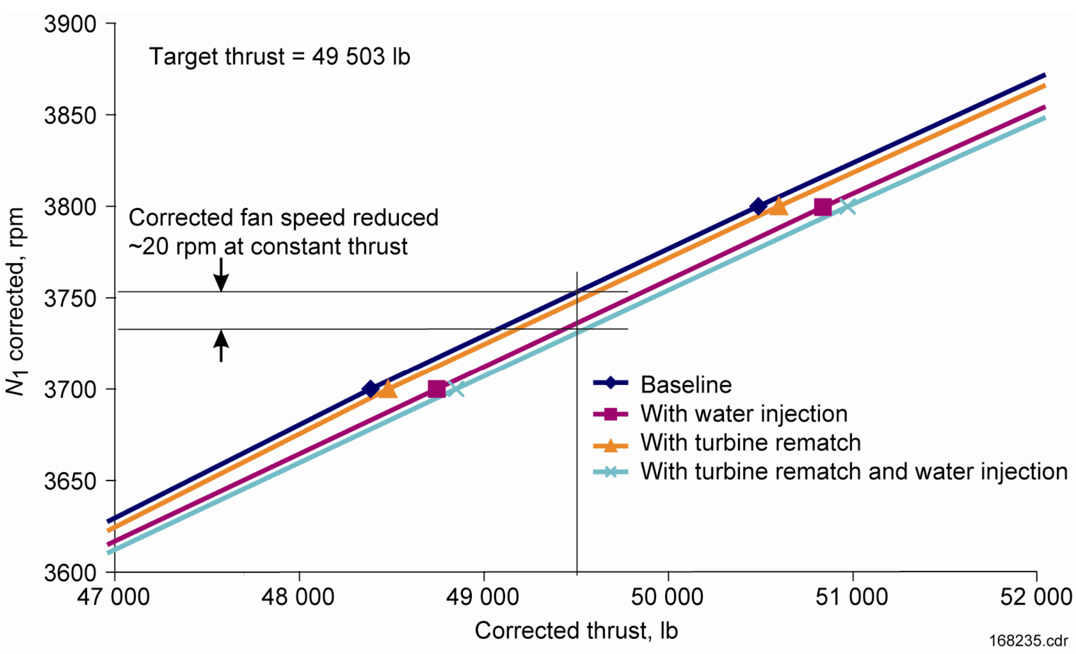


Figure 13.—Impact of turbine rematch and water injection on corrected fan speed N_1 at sideline noise point for Boeing 747–400ER aircraft with PW4062A engine.

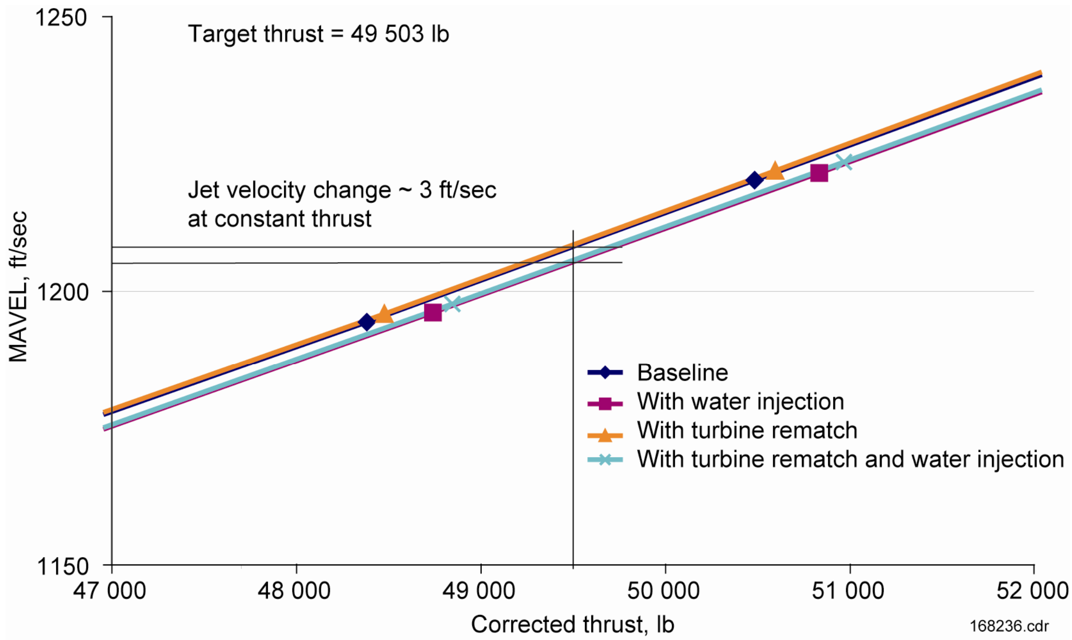


Figure 14.—Impact of turbine rematch and water injection on mass-averaged jet velocity (MAVEL) at sideline noise point for Boeing 747–400ER aircraft with PW4062A engine.

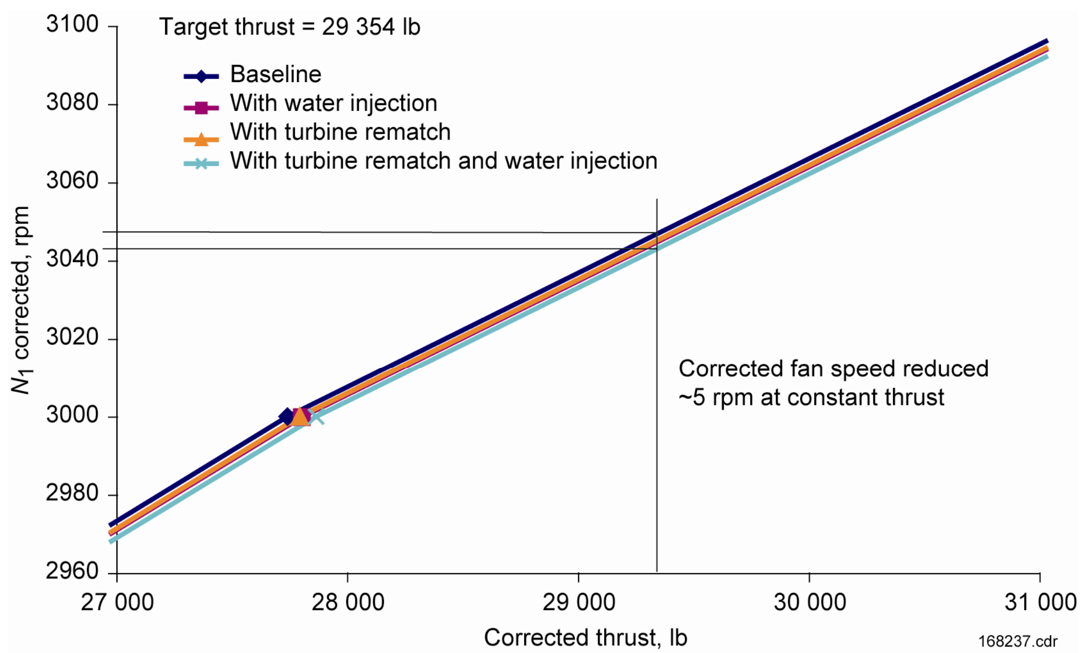


Figure 15.—Impact of turbine rematch and water injection on corrected fan speed N_1 at cutback noise point for Boeing 747–400ER aircraft with PW4062A engine.

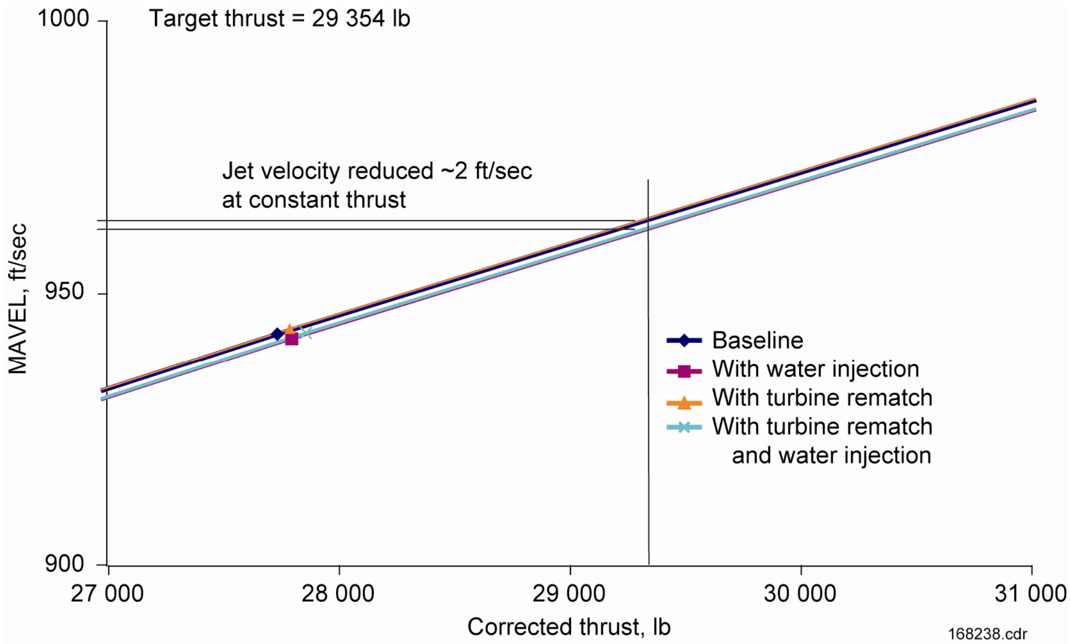


Figure 16.—Impact of turbine rematch and water injection on mass-averaged jet velocity (MAVEL) at cutback noise point for Boeing 747–400ER aircraft with PW4062A engine.

12.0 Performance Analysis of Water Injected in Front of LPC

Simulation modeling is used to evaluate the effect of water injection on engine performance.

12.1 Performance Simulation Model

The PW4062A performance simulation model was also modified for this study to incorporate the capability to inject water directly in front of the LPC. Again, the model assumes that water injected into the gaspath is totally evaporated at the point of injection, and there is 60 percent relative humidity (normal humidity model) in addition to the injected water. Limited data was available to compare this modeling technique relative to actual measured engine data. It is expected that water would actually evaporate as it passed through several stages of LPC compression. Therefore, this modeling technique may not be a realistic method to assess gas generator performance impacts for water injected at the LPC entrance. The performance estimates provided in this report for LPC water injection are included for study purposes only.

12.2 Predicted Impact of LPC Water Injection on Engine Performance

Simulations were run for a number of takeoff conditions to evaluate the shift in parameter levels expected to result from water injection. While running these simulations, thrust was maintained constant for specific ambient temperature, mach number, and altitude conditions while the amount of water injected was varied from zero up to a water-to-local-airflow ratio equivalent to 0.027:1.

The predicted shifts in T_3, $T_{4.1}$, N_1, N_2, $T_{4.9}$, PB, W_f, and EPR resulting from water injection into the front of the LPC under SLS standard day takeoff conditions are plotted as a function of the ratio of water to local airflow in figures 17 and 18. Much larger drops in $T_{4.9}$ and T_4 result when water is injected into the front of the LPC than for injection directly into the combustor. The $T_{4.9}$ decreases linearly with increases in the ratio of water to local air with a reduction of up to 180 °F occurring at a ratio of 0.017:1 (the water injection level that provides a 1:1 water-to-fuel ratio as used for water injection into burner). This results in a reduction in T_4 of approximately 340 °F. The model also predicts a 2.8-percent drop in N_1 with a corresponding 3.6-percent drop in N_2 at a 0.017:1 water-to-local-airflow ratio.

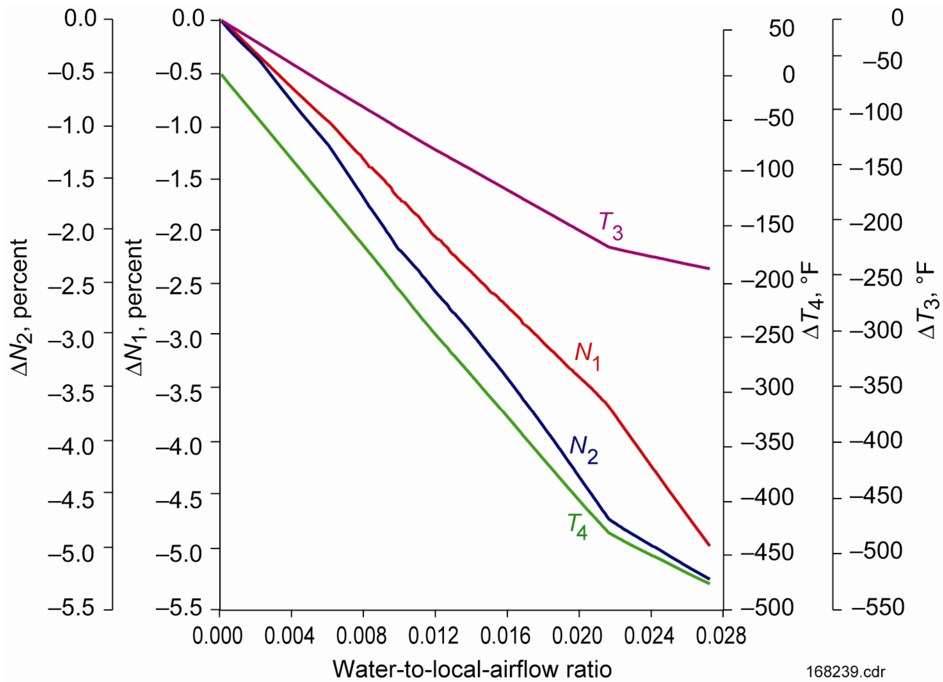


Figure 17.—Predicted impact of water injection into low-pressure compressor entrance of PW4062 aircraft engine at constant thrust: changes in high rotor speed N_2, low rotor speed N_1, high-pressure compressor exit temperature T_3, and combustor exit temperature T_4.

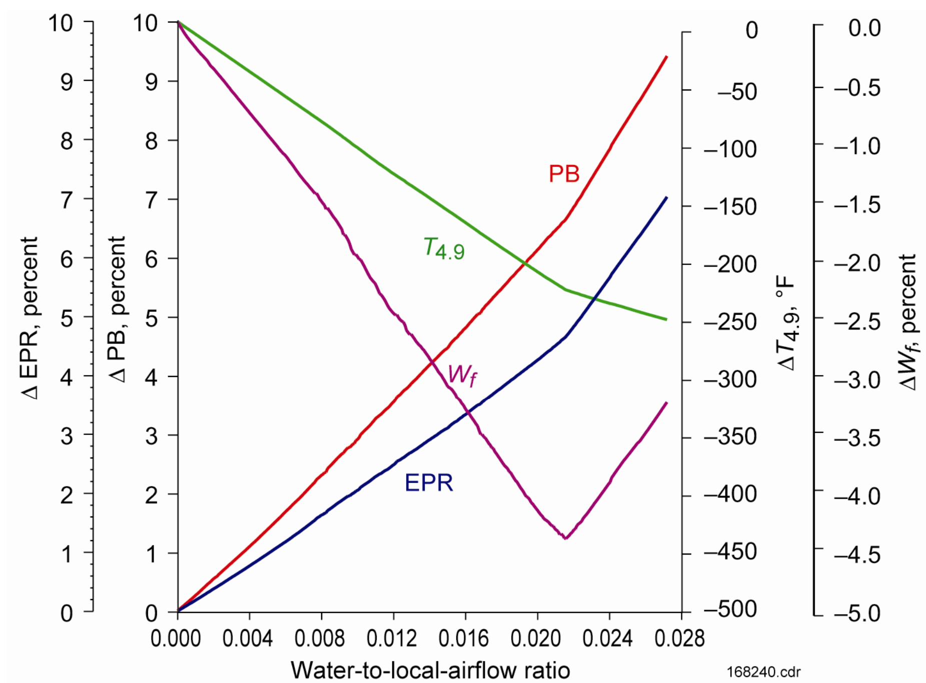


Figure 18.—Predicted impact of water injection into low-pressure compressor entrance of PW4062 aircraft engine at constant thrust: changes in engine pressure ratio (EPR), burner pressure (PB), fuel flow W_f, and low-pressure turbine exit temperature $T_{4.9}$.

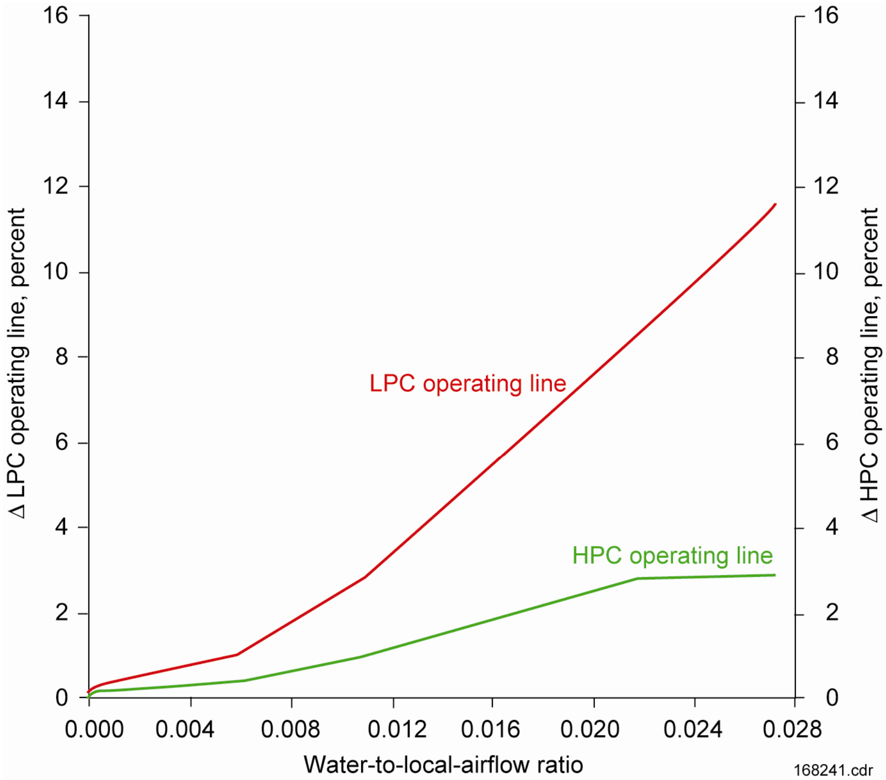


Figure 19.—Predicted impact of water injection into low-pressure compressor entrance of PW4062 aircraft engine at constant thrust: percent changes in low-pressure compressor (LPC) and high-pressure compressor (HPC) operating lines.

12.3 Predicted Impact of LPC Water Injection on LPC and HPC Operating Lines

The shift in LPC and HPC operating lines predicted to result from water injection into the LPC entrance under SLS standard day conditions is plotted as a function of water-to-fuel ratio in figure 19. The model predicts a dramatic increase in LPC operating line of nearly 6 percent at a water-to-air ratio of 0.017:1. The HPC operating line increases 2.0 percent at this same water injection level.

Accommodation of these operating line shifts would necessitate HPT rematch similar to the combustor-injected case, and also a major redesign of the LPC and LPT as well, with the attendant costs of recertification and new hardware. For this reason, and the relative uncertainty of the analysis as mentioned above, we have not pursued the LPC water injection concept.

13.0 Conclusions

The appropriate water-to-fuel ratio of 1:1 has been selected for evaluation primarily as a result of flame stability considerations. NO_x emissions for the current PW4062 (Pratt & Whitney, East Hartford, CT) at this water-to-fuel ratio are likely to be reduced between 30 to 60 percent in Environmental Protection Agency parameter (EPAP). A significant combustor development effort would be required to adapt and validate the combustor for water-fuel injection, to ensure that the combustor meets all system operability and performance, as well as emissions requirements.

At the 1:1 water-to-fuel ratio, the PW4062 should run 120 °F lower in combustor exit temperature, which should enable a 29-percent longer high-pressure turbine (HPT) airfoil life and reduce maintenance cost by $22 per EFH. However, the injection of water at this ratio into the combustor will cause a reduction in low- and high-pressure compressor (LPC and HPC) stability margins of 0.4 and 1.6 percent, respectively, that must be mitigated by a resizing of the LPT (low-pressure turbine) and HPT flow areas. The electronic engine control will also need to be enhanced with a means for determining that water injection is in use and then reschedule the power setting tables accordingly to accommodate the anticipated engine pressure ratio- (EPR-) at-constant-thrust shift.

The addition of the water feed and distribution system would require modifications to the fuel system as well as the addition of a water distribution system and would be priced on the order of $375,000 per engine and add roughly 70 lb in weight. Further, there would be development work for the retuning of the turbine and the certification of the combustor with water injection. The nonrecurring costs associated with this could be on the order of $50 million. Then the turbine would have to be upgraded, preferably at an appropriate overhaul so the additional recurring cost is minimized. See also the sales cost recovery discussion in section 10.0, System-Level Impacts.

While it is technically feasible to build and install a water injection system on existing PW4062 engines, and significant improvements in NO_x emissions and maintenance costs would be obtained, there would be significant nonrecurring costs associated with the development and certification of the system that may drive the system price beyond affordability.

Appendix
Acronyms and Symbols

BOM	bill of material
COTS	commercial off the shelf
EFH	engine flight hour(s)
EGT	exhaust gas temperature ($T_{4.9}$)
EGV	exit guide vane
EI	emission index
EPAP	Environmental Protection Agency parameter
EPR	engine pressure ratio ($P_{4.9}/P_2$)
FDV	flow divider valve
FMU	fuel metering unit
HC	hydrocarbon
HPC	high-pressure compressor
HPT	high-pressure turbine
LDI	lean direct injection
LDW	landing weight
LPC	low-pressure compressor
MAVEL	mass-averaged jet velocity
N_1	low rotor speed
N_2	high rotor speed
NLR2A	fan corrected speed
NO_x	oxides of nitrogen
P_{125}	fan exit pressure
P_2	core engine inlet pressure, ahead of fan
P_{25}	low-pressure compressor exit pressure
P_3	high-pressure compressor exit pressure
P_4	combustor exit pressure
P_{45}	high-pressure turbine exit pressure
PB	burner pressure
SLS	sea-level static
SVR	shop visit rate
T_{125}	fan exit temperature
T_{25}	low-pressure compressor exit temperature
T_3	high-pressure compressor exit temperature
T_4	combustor exit temperature
$T_{4.1}$	high-pressure turbine rotor inlet temperature
$T_{4.9}$	low-pressure turbine exit temperature
T_{45}	high-pressure turbine exit temperature
T_{abs}	maximum gas total temperature (maximum over entire span and circumference)
TBC	thermal barrier coating
$T_{c,\text{ supply}}$	coolant supply temperature
TOGW	takeoff gross weight
T_{rel}	relative gas static temperature (circumferentially averaged, relative to blade)
$T_{rel,\text{ pk}}$	peak relative gas temperature (maximum—corresponding to tabs, relative to blade)
TSFC	thrust-specific fuel consumption
UER	unscheduled engine removal
UHC	unburned hydrocarbons

$W_{2.5R}$	high-pressure compressor inlet airflow
W_{25ILR}	high-pressure compressor inlet airflow with instrumentation installed
$W2AR$	fan inlet airflow
$W_{2\mathrm{R}}$	low-pressure compressor inlet airflow
W_f	fuel flow
WMU	water metering unit

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13. ABSTRACT *(Maximum 200 words)*

This study supports the NASA Glenn Research Center and the U.S. Air Force Research Laboratory in their efforts to evaluate the effect of water injection on aircraft engine performance and emissions. In this study, water is only injected during the takeoff and initial climb phase of a flight. There is no water injection during engine start or ground operations, nor during climb, cruise, descent, or landing. This study determined the maintenance benefit of water injection during takeoff and initial climb and evaluated the feasibility of retrofitting a current production engine, the PW4062 (Pratt & Whitney, East Hartford, CT), with a water injection system. Predicted NO_x emissions based on a 1:1 water-to-fuel ratio are likely to be reduced between 30 to 60 percent in Environmental Protection Agency parameter (EPAP). The maintenance cost benefit for an idealized combustor water injection system installed on a PW4062 engine in a Boeing 747–400ER aircraft (The Boeing Company, Chicago, IL) is computed to be $22 per engine flight hour (EFH). Adding water injection as a retrofit kit would cost up to $375,000 per engine because of the required modifications to the fuel system and addition of the water supply system. There would also be significant nonrecurring costs associated with the development and certification of the system that may drive the system price beyond affordability.

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