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METHODS FOR REDUCING AIR POLLUTION
EMISSIONS DURING JET ENGINE TESTING

THESIS

Jeffrey R. Ullmann, Captain, USAF

AFIT/GEE/ENS/95D-10

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DECISION SUPPORT MODEL TO EVALUATE METHODS FOR REDUCING
AIR POLLUTION EMISSIONS DURING JET ENGINE TESTING

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Engineering and Environmental Management

Jeffrey R. Ullmann, B.S.

Captain, USAF

December 1995

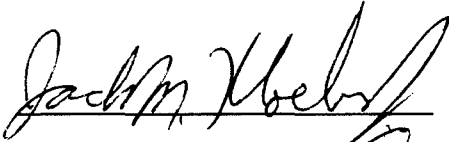
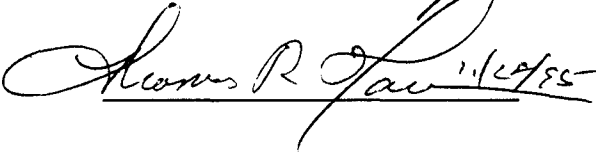
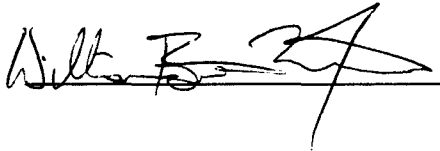
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Captain Jeffrey R. Ullmann

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Abstract

The United States Air Force operates more than 6,800 aircraft that use more than 15,700 turbine engines. Whenever these engines are in operation they generate pollution. The majority of the pollution is composed of five air toxics: Particulate Matter (Smoke), Carbon Monoxide, Oxides of Nitrogen, Oxides of Sulfur, and Unburned Hydrocarbons.

Currently, the emissions from these engines are not regulated while the engines are in use in military aircraft. However, during the periodic maintenance and repair of aircraft turbine engines, maintainers must test the engines' operation at each power setting.

Emissions during these tests are permitted under Title V of the Clean Air Act Amendments of 1990. Because the Air Force has a large number of both engines and engine test facilities, future regulations based on current law have the potential to severely affect the Air Force engine testing program.

This research uses decision analysis to clarify issues surrounding the question: How can Air Combat Command effectively test its jet engines and still comply with the environmental requirements of the Clean Air Act as amended in 1990?

To answer this general question, the research objectives of this study were:

- Perform a review of modern jet engines and the emissions that result from jet engine testing. This review focused on the underlying causes of emissions and potential methods to reduce these emissions.

- Construct a decision model to compare the various existing and potential methods for meeting Clean Air Act regulatory requirements during jet engine testing in ACC.

- Use this model to compare the costs and benefits of various notional methods for meeting regulatory requirements by reducing emissions during the testing of Air Combat Command's jet engines. These notional methods were based on the technologies uncovered during the literature review.

DECISION SUPPORT MODEL TO EVALUATE METHODS FOR REDUCING
AIR POLLUTION EMISSIONS DURING JET ENGINE TESTING

I. Introduction

General Issue

The United States Air Force operates more than 6,800 aircraft that use more than 15,700 turbine engines (Mehuron, 1995:51-54; Young and Taylor, 1995:134-145). Whenever these engines are in operation, they generate pollution. The majority of the pollution is composed of five air toxics:

- PM - Particulate Matter (Smoke)
- CO - Carbon Monoxide
- NO_x - Oxides of Nitrogen
- SO_x - Oxides of Sulfur
- UHC - Unburned Hydrocarbons (Lefebvre, 1983:463).

PM₁₀, CO, NO₂ and SO₂ are criteria pollutants. These criteria pollutants are contained within the five air toxics. Criteria pollutants are air contaminants for which the Environmental Protection Agency has set ambient air quality standards that define the dividing line between acceptable and unacceptable air quality (Griffin, 1994:5-6).

Currently, emissions from commercial aircraft engines are regulated when the engines are in operation. 40 CFR 87.1 defines commercial aircraft engines as “any aircraft engine used or intended for use by an ‘air carrier,’ . . . or a ‘commercial operator’.” However, the Environmental Protection Agency (EPA) and the Department of Transportation (DOT) do not regulate military aircraft engines. 42 USC 7573 states that no State or political subdivision can adopt a standard different from the standard adopted by DOT.

Once an engine is removed from the aircraft and placed in a permanent structure for testing, the rules change. The EPA lists engine test facilities as a major source of air pollution under Section 112(c) of the Clean Air Act as amended in 1990 (EPA, 1992:31591). As a major source, their emissions can be regulated (CAAA, 1990:7412(d)).

During the periodic maintenance and repair of aircraft turbine engines, maintainers must test the engines’ operation at each power setting. Currently these tests occur in three different structures: test cells, test stands, and hush houses. A test cell is an enclosed structure designed to withstand the vibrations, back pressure, and heat generated by the engines being tested. A test stand is a facility most often used for long-term durability testing of uninstalled engines. A hush house is a facility designed to allow the engine to be tested while still installed in the aircraft. Not all hush house testing is performed on installed engines. Uninstalled engines can also be placed on engine mounts within a hush house and tested.

Because the Air Force has a large number of both engines and engine test facilities, future regulations based on current law have the potential to affect the Air Force engine testing program severely. Air Combat Command (ACC), as a major operator of military aircraft, is particularly concerned about the possible future impacts on cost and operations (Isaacs, 1995).

Research Question

Understanding that the Air Force must continue to test its jet engines, the central question of this research is: How can Air Combat Command efficiently test its jet engines, comply with the environmental requirements of the Clean Air Act as amended in 1990, and maintain operational effectiveness?

Research Goals

To answer this general question, the research goals of this study are to:

1. Perform a review of modern jet engines and the emissions that result from jet engine testing. This review will focus on the underlying causes of emissions and potential methods to reduce these emissions.
2. Construct a decision model to compare the various existing and potential strategies for meeting Clean Air Act regulatory requirements during jet engine testing in ACC. This model will focus on four major objectives:

- Minimize negative operational impact,
- Maximize the environmental benefits,
- Minimize the cost of the strategy, and
- Identify the time it will take to field the strategy.

3. Use this model to compare the costs and benefits of various notional methods for meeting regulatory requirements by reducing emissions during the testing of Air Combat Command's jet engines. These notional methods will be based on the technologies uncovered during the literature review. This goal will be met by identifying potential emission reduction strategies surrounding the F110 engine. Block 50 and Block 52 F-16 fighter aircraft use this engine.

II. Literature Review

Overview

First, this chapter discusses the legal and regulatory requirements surrounding jet engine testing. Second, it identifies jet engine testing requirements. Third, it describes the pollution generated by jet engine testing using a process map. Fourth, this chapter explains how jet engines create pollution during testing. Finally, it gives a brief description of various methods that have the potential to lower emissions during tests.

Legal and Regulatory Requirements

Before discussing the specific legal and regulatory requirements surrounding jet engine testing, a look at the overall structure and history of air pollution control legislation is appropriate. This overall framework can help one better understand state and Federal regulatory action toward jet engine testing. Air pollution control legislation can be grouped into: Pre-1970 legislation, the 1970 Clean Air Act along with the 1977 Amendments, and the Clean Air Act Amendments of 1990.

Pre-1970 Air Pollution Control Legislation. From the founding of the United States, until the passage of the Clean Air Act Amendments of 1970, local governments, the States, and the Federal government worked to define each of their roles in regulating air pollution. Initially, common law nuisance and trespass suits resolved air pollution disputes (Stern, 1982:44). Once it became apparent that common law was not enough to control

the increases in pollution, the States began passing individual state laws in the early 1950's.

Starting with the Air Pollution Control Act of 1955, the federal government began to play a role in air pollution control. Throughout the 1950's and 1960's, Congress passed air pollution control laws that emphasized research. In 1965, Congress directed that the Secretary of Health, Education, and Welfare (HEW) set emission standards for motor vehicles (Portney, 1990:30).

The 1967 Air Quality Act (AQA) set the basic framework for the 1970 Clean Air Act Amendments and for later Laws that regulate stationary sources like jet engine test cells.

The AQA did four basic things:

- It provided funding to the States to continue the fight against air pollution.
- It required states to establish Air Quality Control Regions (AQCRs) which grouped together geographic areas that shared air quality control concerns.
- HEW was to investigate and publish information about the adverse health effects of air pollution.
- HEW was to assist States by identifying pollution control techniques so that the States could begin regulating polluters (Portney, 1990:30).

The 1970's. President Nixon heralded the 1970's as the environmental decade. Three major events of 1970 emphasized this new commitment to the environment. First, on 1 January 1970, President Nixon signed the National Environmental Policy Act into law.

Second, on 2 December 1970, the Environmental Protection Agency was formed. Third, on 31 December 1970, President Nixon signed the Clean Air Act Amendments of 1970. These amendments are generally called the Clean Air Act (CAA).

The major goal of the CAA was that the nation's air was to be cleaned up by July 1975. To support this goal, the Act contained many provisions. Some of these provisions affected regulations concerning jet engine testing emissions. These provisions are as follows:

- Money was authorized to conduct additional research
- State and regional grants were authorized
- The EPA was directed to set National Ambient Air Quality Standards (NAAQS)
- Air Quality Control Regions (AQCRs) were designated
- States were directed to write and implement State Implementation Plans (SIPs)

within three years

- New Source Performance Standards (NSPS) were established.
- National Emission Standards for Hazardous Air Pollutants (NESHAPS) were

established, and

- The EPA was to establish aircraft emission standards (Hauser, 1995).

This last provision is significant because it was the first time that Congress specifically addressed aircraft emissions. Figure 1 contains an excerpt from this section of the Act.

Sec. 11. (a) (1) Title II of the Clean Air Act is amended by adding the end thereof the following new part:

“Part B-- Aircraft Emission Standards

“ESTABLISHMENT OF STANDARDS

“Sec. 231. (a) (1) Within 90 days after the date of enactment of the Clean Air Act Amendments of 1970, the Administrator Shall Commence a study and investigation of emissions of air pollutants from aircraft in order to determine --

“(A) The extent to which such emissions affect air quality in air quality control regions throughout the United States, and

“(B) The technological feasibility of controlling such emissions.

[Paragraph (a)(2) and paragraphs (b) and (c) omitted]

“Sec 232. (a) The Secretary of Transportation, after consultation with the Administrator, shall proscribe regulations to insure compliance with all standards proscribed under section 231 by the Administrator. . .

[Paragraph (b) omitted]

“STATE STANDARDS AND CONTROLS

“Sec 233. No State or political subdivision thereof may adopt or attempt to enforce any standard respecting emissions of any air pollutant from any aircraft or engine thereof unless such standard is identical to a standard applicable under this part.

Figure 1 Excerpt from the Clean Air Act Amendments of 1970 (CAA, 1970).

In 1977, Congress again revisited the Clean Air Act. On 7 August 1977, President Carter signed The Clean Air Act Amendments of 1977 into law (Stern, 1982:58). The 1977 Amendments retained the basic approach to air pollution control adopted in 1970. However, some additional provisions were added that had an impact on jet engine testing emissions regulations. These provisions are as follows:

- Conditions were placed on the construction of new sources or on the modification of major sources.
- The EPA was to permit the construction or modification of major sources in both non-attainment and non-degradation areas.
- The policy of emission off-sets was established, and

- The concept of prevention of significant deterioration (PSD) was established (Hauser, 1994).

While none of the provisions of the 1970 and 1977 Acts was directed specifically at jet engine test cells, these laws laid the groundwork for the Clean Air Act Amendments of 1990 that directly impact the permitting and operation of jet engine test cells.

The Clean Air Act Amendments of 1990. On 15 November 1990, President Bush signed the Clean Air Act Amendments of 1990 (CAAA) into law. The bill passed the House by a vote of 401 to 21 and the Senate by a vote of 89 to 11. The 1990 Amendments represented significant change to the nation's clean air policies (Hauser, 1994). Of particular significance to jet engine testing emissions are the following provisions:

- **The Attainment and Maintenance of National Ambient Air Quality Standards under Title I.** The fact that the Air Quality Control region a test cell is located in is in or out of compliance can be a major factor in the emission levels allowed by the test cell's Title V permit.

- **The listing of major source categories under Title III.** The Environmental Protection Agency (EPA) lists engine test facilities as a *major source* of air pollution under Section 112(c) of the Clean Air Act as amended in 1990. As a major source, their emissions can be regulated.

- **The permitting program under Title V.** Title V gives States the ability to issue federally-enforceable permits for major emission sources (Griffin, 1994:331).

Permits written under Title V can directly affect the operations of jet engine test cells at Air Force bases (Senn, 1994).

Engine Testing Requirements

Even though the CAAA of 1990 can severely limit the permitted emission levels from jet engine test cells, the United States Air Force has more than 15,700 turbine aircraft engines that must be tested after periodic maintenance and repair. The Technical Order (TO) for the F110-GE-129 provides an example of the testing requirements. This TO requires engine testing following “component replacement or maintenance” (DAF, undated:5) Currently these tests occur on the aircraft, in partially enclosed engine test stands, in test cells, or in enclosed facilities called hush houses. Figure 2 shows the typical configuration of a test cell or hush house.

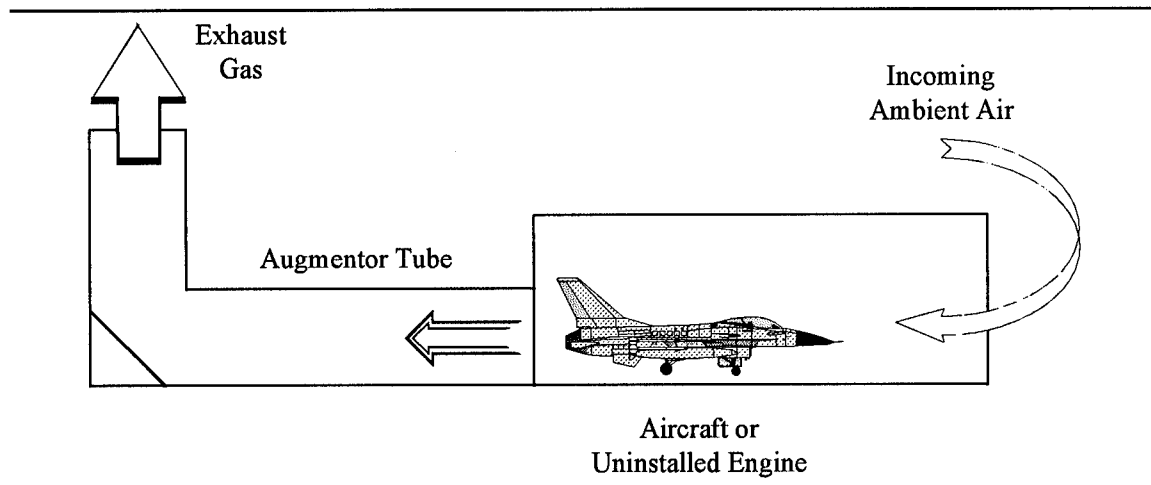


Figure 2 Typical Test Cell or Hush House Configuration

Process Map

Before examining potential methods for reducing emissions during jet engine testing, a brief description of the process that generates these emissions is needed. From a macroscopic viewpoint, the jet engine testing process can be broken down into three parts: the pre-combustion inputs, fuel and the ambient air; the engine itself; and post-combustion exhaust (See Figure 3 below).

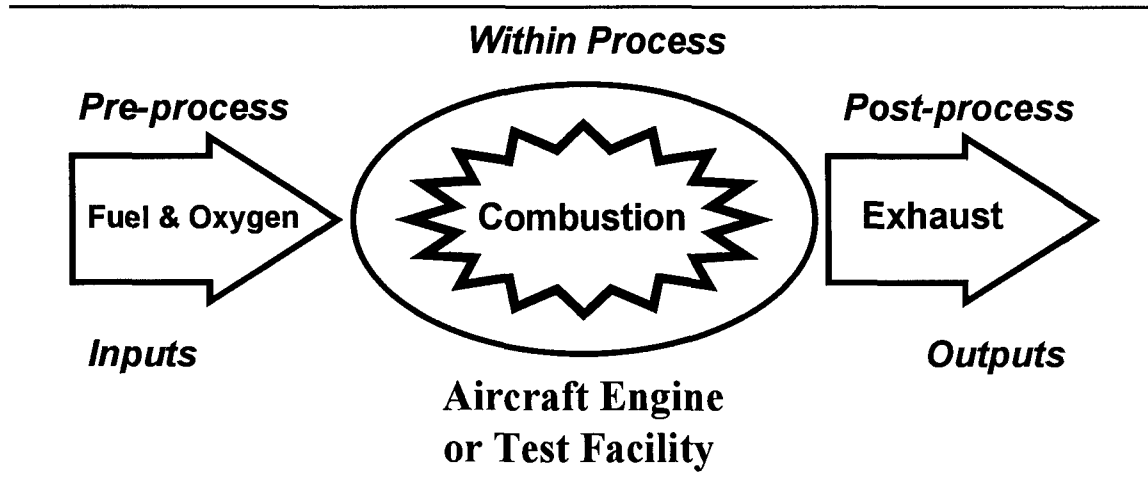


Figure 3 Engine Testing Process Map

The pre-process (input) phase is composed of aviation fuel and oxygen. Aviation fuel is “the source of energy required for the propulsion of airborne vehicles. This energy is released as heat and expanding gases that are the products of a combustion reaction that occurs when fuel combines with oxygen from the ambient air” (Pangborn, 1992:284). Currently, the Air Force is converting all of its aircraft to JP-8 fuel from the more explosive JP-4 fuel. This conversion is scheduled to be completed by the end of 1996 (Keil, 1995).

The process phase of jet engine testing occurs in the engine itself. In this phase, the fuel and oxygen are combined and burned. The typical turbojet engine is composed of several sections: the inlet system, the compressor, the combustor, the turbine, and the exhaust nozzle. The inlet system takes in air at the speed the aircraft is traveling and slows the air to a speed that can be drawn into the compressor (Ehrich, 1992:628-629). Once in the compressor, the air is compressed adiabatically. The combustor adds heat by burning fuel at a constant pressure. After passing through the combustor, the hot gas passes to the turbine. In the turbine, the gas expands providing energy to the turbine that drives the compressor. Once the expanding gas leaves the turbine, it continues to expand in the jet nozzle where the remaining energy is converted into thrust (Blanton, 1992:474-475).

In addition to the typical five sections already described, many military fighter aircraft jet engines also have an afterburner stage that is used to augment engine thrust during short periods when increased thrust is required, such as during combat (Ehrich, 1992:629). The afterburner stage is located between the turbine and the jet nozzle. In this stage, additional fuel is burned to provide increased thrust when needed (Pinkel, 1992:170).

In the post-process phase, the results of combustion are exhausted to the ambient air. Each of these phases provides an opportunity to reduce the volume of pollution released during jet engine testing.

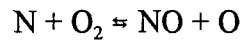
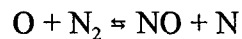
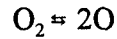
Mechanism of Pollutant Formation

During the combustion phase, PM, UHC, CO, SO_x and NO_x are created. Before discussing possible methods for reducing this pollution, it is useful to understand the underlying mechanisms that create these air toxics. This section discusses the health effects of the five air toxics of concern and how jet engines generate these air toxics. Additionally, this section will describe how some of these pollutants react to form tropospheric ozone, another criteria pollutant.

Oxides of Nitrogen. The pollutants of greatest concern during jet engine testing are the oxides of nitrogen. The emission of the oxides of nitrogen is important because nitrogen dioxide is a criteria pollutant. Nitrogen dioxide is a concern for two reasons. First, NO₂ is a precursor to tropospheric photochemical ozone whose formation and health effects are discussed later. Second, nitrogen dioxide has its own set of negative health effects. The acute effects of NO₂ are direct damage to the lung cell membranes and airway constriction (Griffin, 1994:28). The chronic effects of NO₂ include necrosis, or direct cell death (Griffin, 1994:28).

The oxides of nitrogen are formed during the operation of turbine engines through three different chemical processes: thermal NO, prompt NO, and fuel NO.

- The oxidation of atmospheric nitrogen produces Thermal NO in the post flame gases. This reaction occurs according to the well established Zeldovich chain mechanism (Lefebvre, 1983:469). These chemical reactions are:



- Prompt NO is produced in the early flame region of the combustor in low-temperature, fuel-rich flames (Lefebvre, 1983:470).
- Fuel NO results from the oxidation of the nitrogen contained in the jet fuel (Lefebvre, 1983:469).

These three processes account for the formation of NO. NO is oxidized to NO₂ once the exhaust gasses begin to cool after leaving the jet engine (Lefebvre, 1983:473).

Particulate Matter. Fine particulate matter can cause several acute health problems. These problems include increased mortality rates, incidents of asthma, and respiratory disease (Griffin, 1994:27). In addition to the acute health effects, long term exposure to fine particulates can result in reduced lung capacity and lung scarring (Griffin, 1994:27).

Particulate matter is found in the smoke exhaust of jet engines. Smoke can be generated in fuel-rich zones in the combustor where mixing is inadequate (Lefebvre, 1983:473).

Five main factors control soot formation. These factors are the specific properties of the fuel, the combustion temperature and pressure, the fuel/air ratio, atomization quality, and the injection mode (Lefebvre, 1983:475).

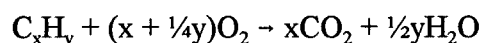
Carbon Monoxide. Carbon monoxide is a criteria pollutant. Consequently, carbon monoxide emissions are subject to regulation. Carbon monoxide can cause asphyxiation. Also, it can impair performance, slow reflexes, and cause fatigue and headaches (Griffin, 1994:29).

If the gas turbine combustor is operating fuel-rich, then large amounts of carbon monoxide will form. This is because a fuel-rich environment does not contain enough oxygen for the fuel to react completely to CO₂. However, if the air-to-fuel ratio is stoichiometric or moderately fuel-lean, then a significant amount of CO will be present because of the disassociation of CO₂ (Lefebvre, 1983:467). Actual CO emissions are much higher at low power settings. This suggests that incomplete fuel combustion generates much of the carbon monoxide (Lefebvre, 1983:467).

Oxides of Sulfur. The oxides of sulfur (SO_x) are a concern because of the criteria pollutant sulfur dioxide (SO₂). The acute health effects of SO₂ include a variety of respiratory ailments. SO₂'s chronic effects include immune system suppression and increased risk of bronchitis (Griffin, 1994:27).

SO_x emissions are composed mainly of SO₂ and SO₃. These compounds are formed when the sulfur contained in the jet fuel combines with oxygen from the ambient air (Lefebvre, 1983:463). Because almost all of the SO_x comes from sulfur in the jet fuel, the only effective way to prevent SO_x from forming is to reduce the sulfur content of the fuel.

Unburned Hydrocarbons. Unburned hydrocarbons (UHC) “include fuel that emerges at the combustor exit in the form of droplets or vapor, as well as the products of the thermal degradation of the parent fuel into species of lower molecular weight, such as methane and acetylene” (Lefebvre, 1983:469-469). Under ideal conditions, a hydrocarbon fuel, such as jet fuel, would oxidize completely to CO₂ and water when burned. For complete oxidation to occur, a precise air-fuel ratio must exist. This ratio, with no excess oxygen, is called a *stoichiometric* mixture (Seinfeld, 1986:77). The required ratio is found in the following chemical reaction:



When this condition does not exist, products of incomplete combustion result.

Ozone. Ozone is also a criteria pollutant that can cause damage to the respiratory system. Ozone’s acute effects include “cough and chest pain, eye irritation, headaches, lung function losses, and asthma attacks” (Griffin, 1994:27). “Chronic exposures to elevated ozone levels are responsible for losses in immune system functions, accelerated aging and increased susceptibility to other infections” (Griffin, 1994:27).

Although ozone is a pollutant of concern, it is not directly emitted to the ambient air during jet engine testing. The reason it is a pollutant of concern is that several pollutants emitted during engine tests are precursors to ozone. These pollutants include the oxides of nitrogen, carbon monoxide, and unburned hydrocarbons. Figure 4 shows the set of chemical reactions that lead to ozone formation. These chemical reactions show why NO_x, CO and unburned hydrocarbon emissions are of such concern. These reactions are

not limited to the HO· and HO₂· radicals. Any RO· or RO₂· radical (where R is any alkyl group) can be substituted into these reactions (Seinfeld, 1989:745). A source of these radicals is unburned hydrocarbons.

Ozone is the major cause for air quality control regions not meeting compliance standards. The need for these regions to comply drives the levels of emissions allowed by permit. These emissions are more tightly controlled in ozone non-attainment areas because they add to the formation of ozone. Tight permitting requirements can lead to limits on the amount of jet engine testing allowed at a given installation.

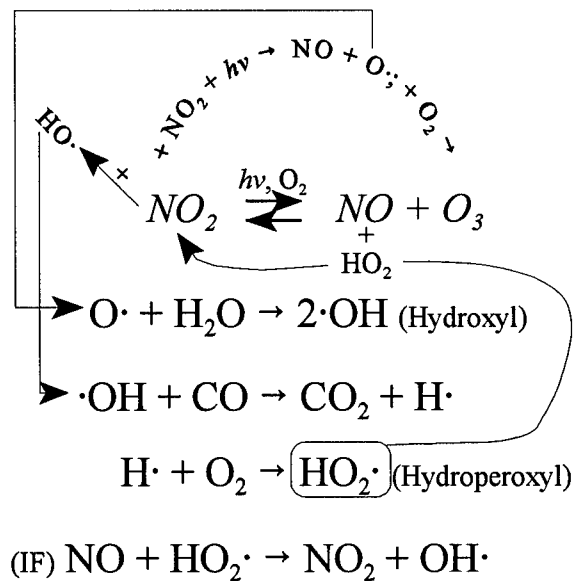


Figure 4 The Ozone Formation Reaction (Hauser, 1994)

Emission Reduction Methods

Each phase of the jet engine testing process provides opportunities for emission reduction. The pre-process phase offers the opportunity for different fuel or fuel additives to reduce emissions. The process, the engine itself, could be modified or replaced. Or, a

post-process control technology could be placed between the engine and the ambient air during testing. This section will look at each of these process phases to see what research and development has been done in the past and what additional research may prove promising in the future.

Fuels. The pre-process inputs are fuel and air. However, the type of aviation fuel used is the only controllable input. The air is the air and must be taken as is. The amount of different chemical compounds in the ambient air is uncontrollable. While the following alternative fuels may not be applicable to military jet engines, a short discussion of the different alternative fuels discussed in the literature is appropriate.

JP-8. Over the last several years, the Air Force has converted from jet fuel type JP-4 to JP-8. JP-8 fuel is less volatile than JP-4. JP-8 has been used in USAFE and PACAF for many years but the conversion to JP-8 in the United States will not be completed until 1996 (Nault, 1995).

JP-8+100. JP-8+100 consists of standard JP-8 fuel mixed with an anti-coking additive package consisting of antioxidants, metal deactivators, dispersants, and detergents. The additive package is added to JP-8 fuel at a concentration at parts per million. (Martin, 1995:2) The purpose of JP-8+100 fuel is to give the fuel an additional 100 degrees Fahrenheit of thermal stability. This increased thermal stability is needed because the Air Force has seen an increase in fuel coking within its jet engines since the conversion from JP-4 to JP-8 fuel (Martin, 1995:1).

Although reducing emissions is not a goal of the JP-8+100 program, a reduction of carbon monoxide and hydrocarbons may be an added bonus of using this fuel. The additive package may actually improve the combustion process, reducing much of the exhaust gas to carbon dioxide and water. Wright-Laboratories will conduct testing to confirm this phenomenon (Keil, 1995).

Methanol(Ethanol)/JP-8 Blend. The use of methyl or ethyl alcohols either as a stand-alone substitute, or as a blend with conventional jet fuel, presents an attractive environmental option to conventional turbine aircraft fuel (Price, 1994:6). The use of methanol to fuel commercial jet aircraft has several potential environmental benefits:

Significant reduction in NO_x emissions relative to conventional Jet A, negligible particulate emissions [and], Reduced emissions of carbon monoxide and aldehydes during full power operation, such as take-off and climb-out, with a possibly slight increase in these emissions during low power operation, such as descent and taxi (Price, 1994:6).

One drawback of methanol as a turbine aircraft fuel alternative is that it would result in an aircraft range reduction of approximately 50% if one looked at only the BTU content of the fuel. However, the fuel has the potential to increase turbine power and mass flow which results in the ability to operate at decreased power, increased altitude, or increased air speed. These factors would have a positive effect on range (Price, 1994:6). The effects of ethyl alcohol (ethanol) are similar to those of methanol. The overall effect of the fuel blend on engine performance would be engine and aircraft specific.

Water/Steam Injection. Water or steam injection is an established NO_x reduction method for stationary gas turbines. Water lowers the flame temperature, which

in turn decreases the thermal formation of NO_x . To use this method that lessens the formation of NO_x , the engine being tested, would require temporary modification that would significantly alter its performance characteristics (EPA, 1994:1-10). After the test is complete, the engine must be returned to its unmodified state before it can be returned to operational service. Using this method to decrease NO_x emissions would defeat the purpose of certification and validation testing since the engine being tested would not be in its operational configuration (EPA, 1994:1-11).

Water-In-Fuel Emulsion. Water-in-fuel emulsion would have similar benefits and drawbacks as the water/steam injection. It would reduce emissions, but the engine would not be tested in its operational configuration (EPA: 1994, 1-11).

Engine Modifications. Currently, engine manufacturers are developing new types of combustors for aviation turbine engines. Combustion modifications for commercial jet engines include a goal of reduced emissions, because both the Environmental Protection Agency and the International Civil Aviation Organization regulate these engines. New military engines, on the other hand, are being developed for reduced weight and increased thrust. Any environmental benefits, by the way of reduced emissions, will be an added bonus on top of the increased performance characteristics of the new engines (Keil, 1995). Several new engine technologies are discussed below.

Rich/Quench/Lean (RQL) Combustion. "The rich/quench/lean (RQL) combustion concept has demonstrated a significant reduction in NO_x formation in gas

turbine applications” (Rizk and Mongia, 1991:1). This combustion method takes advantage of the fact that a fuel-rich combustion zone is effective in reducing NO_x . The disadvantage of fuel-rich combustion is that CO, UHC and soot are formed in large quantities because of the lack of oxygen needed to complete the combustion reactions that result in CO_2 and H_2O . The RQL method is effective because it overcomes this disadvantage when the mixture is uniformly quenched and then sent through a lean-fuel stage. In the lean-fuel stage, the proper stoichiometry exists to complete the oxidation reaction so that most of the CO, UHC and soot from the fuel-rich stage are consumed (Rizk and Mongia, 1991:1).

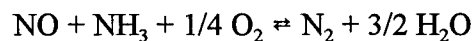
Double Annular Combustor. Turbine engine combustors that use combustion process staging in separate combustion zones have been investigated as a method of reducing NO_x emission levels (Bahr, 1987:182). One example of this type of combustor is the double annular combustor. The double annular combustor has two parallel stages, an outer pilot stage and an inner main stage. The pilot stage is designed for a lower air flow rate than the main stage and is the only stage in use during startup, altitude relight, and idle conditions. In all other modes of operation, the main stage is also in use and the fuel flow is split between the stages (Bahr, 1987:182-183).

Integrated High Performance Turbine Engine Technology (IHPTET). The IHPTET is a cooperative effort of the Army, Navy, Air Force, NASA, Advanced Research Projects Agency (ARPA) and industry development programs. The goal of this

program is to develop turbine engine technology to provide “twice the propulsion capability of today’s systems by around the turn-of-the-century” (WL/POT, 1995).

Test Cell Control Technologies. If changing the fuel or the combustion process cannot prevent jet engine test cell emissions, a control technology is the only option available to lower emissions. Control technologies are under development that have the potential to significantly reduce emissions during jet engine testing. Control technologies, like scrubbers and bag houses, are not useable in jet engine test cells because their back pressure is too high. A back pressure of less than one inch H₂O is desirable (Canfield, 1995). This section will describe five of these technologies.

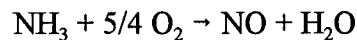
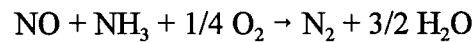
Selective Catalytic Reduction. Selective Catalytic Reduction (SCR) is a post-combustion control technology that can reduce the amount of NO_x released to the ambient air. It is a “highly reaction-specific process to push the reaction of NO with ammonia towards a thermodynamic equilibrium” (EPA, 1994:4-5). The reaction equation is:



Under ideal conditions, the reaction would result in only nitrogen and water emissions. However, because of the highly transient conditions of jet engine testing, the reaction is not complete and some ammonia will be present in the exhaust gasses (EPA, 1994:4-5). Using a catalyst improves this reaction. “Proprietary [catalyst] formulations containing

titanium oxide, vanadium pentoxide, platinum, or zeolite are available to meet a wide range of operational temperatures” (EPA, 1994:4-6). This is important because the temperature of the exhaust gasses during jet engine testing are highly transient as the engine changes from one operational mode to another.

Selective Non-Catalytic Reduction. Selective Non-Catalytic Reduction (SNCR) is another NO_x control technology that can be used in jet engine test cells. SNCR adds chemicals to the exhaust stream that react with NO_x at elevated temperatures to produce molecular nitrogen. Two of the reactive agents are ammonia and urea. The following two competing reactions express the chemistry of the ammonia reaction:



The first reaction is the desired step, causing the reduction of NO to molecular nitrogen. This reaction occurs in a narrow temperature range centered at approximately 1,800 to 2,000F. If the temperature is 100 to 200F over this range, the second reaction dominates, and NO is created (EPA, 1994:4-12-4-13).

Lean Reburn. Lean Reburn is a NO_x emission control technology that uses a duct burner to consume part of the excess oxygen available in the exhaust of the engine test cell. This reduced level of oxygen lowers the amount of NO_x that forms in the exhaust gas (EPA, 1994:4-17).

Vermiculite-MgO Sorbent Bed. This control technology consists of a bed of vermiculite coated with magnesium oxide (MgO) placed at the end of the exhaust gas chimney of the jet engine test cell (Nelson and others, 1992:74). This technology has several benefits:

- The ability to remove 50 to 60 percent of NO_x emissions,
- Removal rates in excess of 50 percent for particulates,
- Removal of small amounts of gaseous hydrocarbon compounds,
- Back pressure less than 1 inch H₂O, and
- The ability to react to changing conditions as the engine is tested in different modes (Nelson and others, 1992:74).

Additionally, the placement of an activated carbon bed in front of the vermiculite-MgO bed increases the NO_x removal rate to at least 80 percent and provides improved removal of gaseous hydrogen compounds (Nelson and others, 1992:75).

Pulse-Corona-Induced Plasmas. Another control technology under development is the pulse-corona-induced plasma. The plasma process “uses a very sharp-rising, narrow-pulse high voltage to a corona system to produce intense streamer coronas generating radical species that react with NO_x” (Durham and others, 1994:ii). Tests have demonstrated many benefits of this control technology:

- Low back pressure,
- The ability to instantaneous adjust the system when the engine changes operational mode,

- The level of NO_x removal is variable up to 90 percent,
- The removal efficiency increases at lower temperatures,
- The process can decompose volatile organic compounds (VOC) in the gas stream, and
- The conditions allow for charging and collecting soot particles (Durham and others, 1994:ix).

What Needs to be Done?

This literature review described the evolution of laws controlling the release of pollutant emissions from jet engine test cells. These laws have become more strict over time. Originally there was no regulation, but now some laws specifically regulate test cell emissions. These emissions are caused by different physical processes. These processes can be affected by pre-combustion inputs, the combustion process, and post-combustion test cell control technology. Each of these phases of the process provides an opportunity for emission reductions. The central question of this thesis -- *How can Air Combat Command efficiently test its jet engines, comply with the environmental requirements of the Clean Air Act as amended in 1990, and maintain operational effectiveness?* -- is complex because of the issues raised in this chapter.

Because of its complexity, this problem is ideally suited to decision analysis. A decision analysis model will clarify the issues surrounding this question and assist Air Combat Command decision makers to make a more informed decision. This approach is in line with Air Force Doctrine Document 42 that states that civil engineers “should provide

decision makers with balanced, objective analysis of the true impacts and costs of alternatives for Air Force operations in meeting environmental goals” (DAF, 1994:2.7).

To this end, the next chapter will model this question using decision analysis.

III. Methodology

Research Methodology

The question of which course of action the Air Force should take to reduce the emissions during jet engine testing is complex. Each alternative must be evaluated using multiple criteria: How will the alternative affect operational and tactical requirements? How will the alternative aid in meeting environmental compliance requirements? How much will it cost? And, when will it be available? Additionally, many alternatives are not mutually exclusive so the number of possible strategies to be considered is large. For this reason, this problem is ideally suited to decision analysis techniques.

A short description of the purposes and techniques of decision analysis is found in Appendix A of this thesis. For a more comprehensive discussion of decision analysis, refer to *Making Hard Decisions: An Introduction to Decision Analysis* by Robert T. Clemen.

The methodology used in this thesis is prescriptive decision analysis. The exact steps used to complete the research are based on the methods suggested by Clemen and the methodologies introduced by Colonel (Ret.) Gregory Parnell (Parnell, 1995). Figure 5 contains a flowchart outlining the steps. This chapter describes the steps used to complete the conceptual decision model. The data collection and analysis of model data will be described in Chapter Four.

Problem Identification

Step 1. Identify the Problem. The first step in any decision problem is identifying the specific problem the decision maker wishes to solve. This is important because incorrectly identifying the specific problem can result in solving the wrong problem. This mistake is often called an “error of the third kind” (Clemen, 1992:5).

The specific problem this research addresses is: How can Air Combat Command efficiently test its jet engines, comply with the environmental requirements of the Clean Air Act as amended in 1990, and maintain operational effectiveness?

Step 2. Identify Objectives. The next step in this methodology is to identify the objectives of the decision maker as they relate to the decision problem and the attribute to measure these objectives. For this question there are four main objectives against which each alternative will be evaluated. They are: **minimize negative operational impact, maximize the environmental benefit, and minimize the cost of the strategy and identify the time it takes to field the strategy.**

- **Minimize Operational Impact.** Operational impact is of great concern to Air Combat Command. The smaller the negative impact an alternative has on aircraft operations, the better. Because the tolerance for negative impact is small, only alternatives with little or no negative operational impact will be considered.

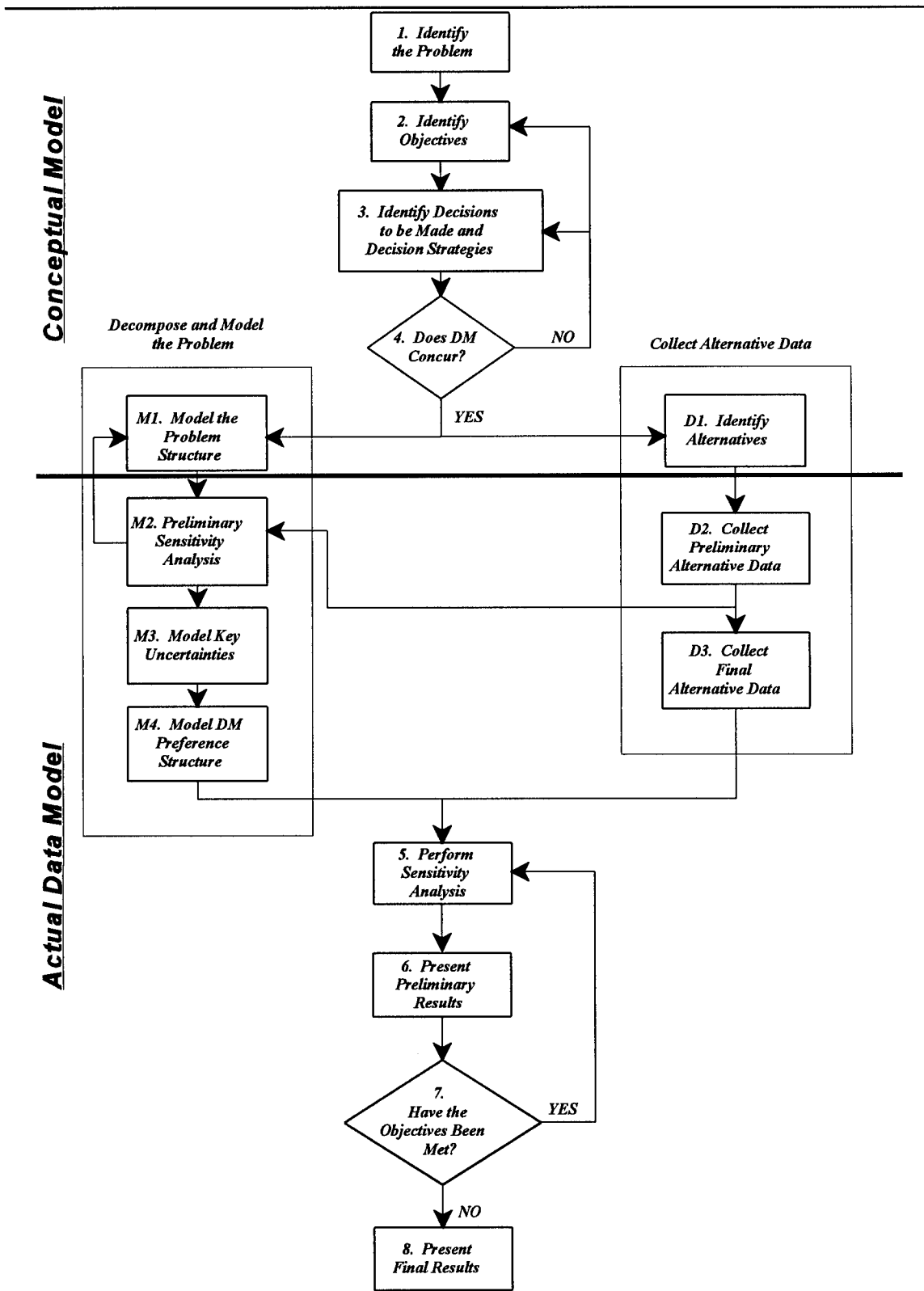


Figure 5 Research Methodology Flowchart

- **Maximize the Environmental Benefit.** The environmental benefit of the strategy is quite important. It is the reason the state and federal regulations address this issue at all. Maximizing the environmental benefit is the primary purpose of the alternative chosen. Because there are currently no specific regulatory requirements for jet engine testing, only individual permits, the preferred alternative would have the greatest environmental benefit.

- **Minimize the Cost of the Strategy.** Cost is an important consideration. Many of these technologies are quite expensive. The cheaper the alternative, the better.

- **Identify the Time It Will Take to Field the Strategy.** Time is a factor that should be considered. Many of the alternatives are currently under development, or involve technologies that have not been applied to military engines or test cells before. Therefore, some alternatives may be available in the near term, while others are projected to be researched and developed and to become available later.

These are the broad general objectives of this decision problem. Later in this chapter, the specific sub-objectives and the attributes of those objectives will be discussed in greater detail. These broad objectives are important because they frame the analysis of the problem.

Step 3. Identify Decisions to be Made and Decision Strategies. After identifying the objectives, the next step is to identify the decisions that must be made to reach these

objectives. A set of decisions can be combined into a decision strategy. In this decision problem there are three decisions to be made:

- **What type of fuel should the Air Force use?**
- **Should the turbine engine itself be modified or replaced?**
- **What, if any, control technology should be applied to the test facilities?**

The options for each of these decisions are listed in the strategy generation table contained in Figure 6. A strategy results when all the decisions are made. The do nothing, or baseline, strategy is circled. This is the strategy the decision maker would choose if he or she choose not to change the current engine test process.

Strategy Generation Table

Strategy	<i>Pre-Process</i>	<i>Within Process</i>	<i>Post-Process</i>
	<i>Fuels</i>	<i>Engine</i>	<i>Control Technology</i>
Baseline Strategy →	JP-8	No Change	No Change

Figure 6 Strategy Generation Table Showing Baseline Strategy

Step 4. Does the Decision Maker Concur? After identifying the specific problem to be solved, the objectives or criteria with which the alternatives will be measured, and the decisions to be made, the analyst should consult the decision maker to ensure that he has captured all of the decision maker's concerns in the objectives and all of the needed

decisions. Of overriding importance is that the analyst has correctly identified the problem.

On 13 April 1995, the decision makers for this research, Mr. Gil Burnet, Mr. Larry Isaacs and Ms. Mary Ruth Senn were contacted to discuss these issues. At that meeting, they agreed to these three decisions and these four objectives (Burnet, 1995; Isaacs, 1995; Senn, 1995). The specific sub-objectives were discussed at a later meeting.

Model Development

Step M1. Model the Problem Structure. Once the decisions and objectives were identified, the next step is to develop the decision model. In this step, influence diagrams and decision trees are used to represent the decision problem. Because the influence diagram for this model is so large, it is broken down into four modules to make the influences more understandable. Figure 7 shows the four major objectives of the problem as they are influenced by the three decisions. In the following sections, each of these objectives is shown as an individual module. Although this research paper shows each module as a separate influence diagram, the problem is actually solved using a single combined model. For a description of the use of nodes and arcs in influence diagrams, refer to Appendix A.

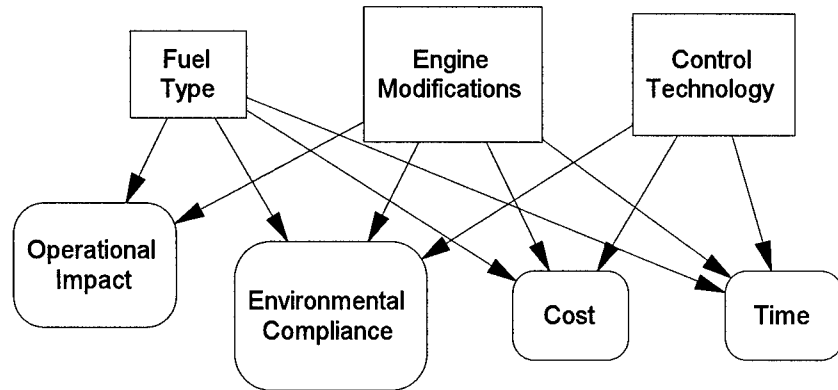


Figure 7 Macroscopic Influence Diagram

Operational Impact. The first module in the model is the operational impact module. The purpose of this module is to measure the negative operational impact produced by the strategy selected. Operational impact is measured from 0 to 100 where 0 represents mission failure and 100 represents no impact. It is possible for a technology to be better than the baseline. Technologies superior to the baseline would receive a score greater than 100. An example might be a new IHPTET engine. These new engines might be environmentally friendly, but they will definitely perform better than current engines because increased performance is the goal of the program. Figure 8 contains the influence diagram representing this module. The three decision nodes: **Fuel Type**, **Engine Modification**, and **Control Technology**, influence the value nodes in the influence diagram.

The **Fuel Type** decision directly influences three value nodes. Each of these nodes is scored by expert opinion where 100 represents no negative impact on current performance and 0 represents mission failure:

- **EP Fuel Impact** -- This node represents the effect on engine performance caused by the fuel type selected. Some of the factors this node takes into account are: BTUs of energy/lb of fuel, potential to leave a coking residue, and specific fuel consumption.

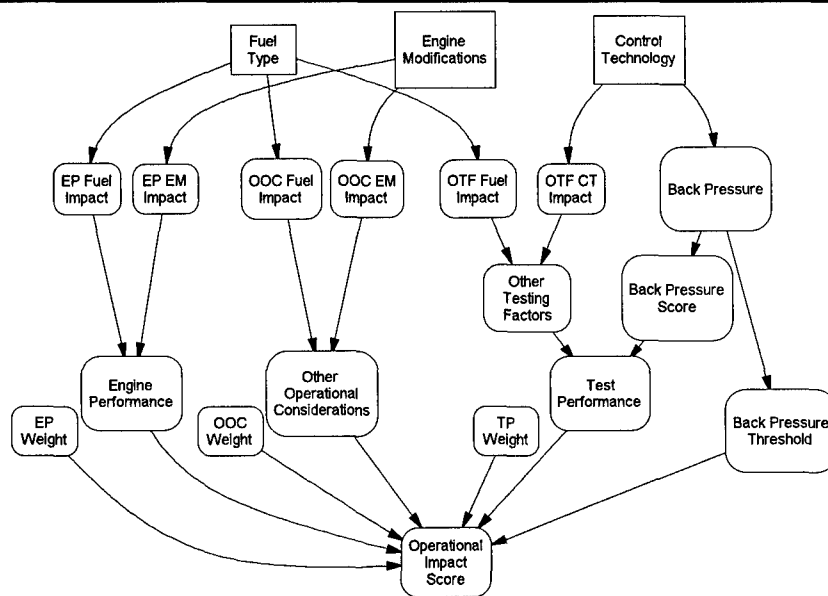


Figure 8 Operational Impact Module Influence Diagram

- **OOC Fuel Impact** -- This node represents the effect on other (non-engine) operational considerations caused by the fuel type selected. Some of the factors this node takes into account are: the fuel's volatility, the handling characteristics of the fuel, the toxicity of the fuel, and the fuel's potential to retain water.

- **OTF Fuel Impact** -- This node represents the effect on other (non-back pressure) testing impacts caused by the fuel type selected. This node should have a score less than 100 only if the fuel used for testing is different from the fuel used in the aircraft. If this is the case then the value of this node would represent the loss, if any, in test accuracy or reliability because of the difference in fuel.

The **Engine Modification (EM)** decision directly influences two value nodes. Each of these nodes is scored by expert opinion where 100 represents no negative impact on current performance and 0 represents mission failure:

- **EP EM Impact** -- This node represents the effect on engine performance caused by the engine modification selected. Some of the factors this node takes into account are: excess thrust (P_s), specific fuel consumption (SFC), total accumulated cycles (TACS), and engine flying hours (EFH).

- **OOE EM Impact** -- This node captures any other operational considerations caused by the engine selected. These considerations would be operational impacts caused by a new engine or engine modification that is not directly related the engine performance.

The **Control Technology (CT)** decision directly influences two value nodes:

- **OTF CT Impact** -- This node represents the effect on other (non-back pressure) testing impacts caused by the control technology type selected. It is scored by expert opinion where 100 represents no negative impact on current performance and 0 represents mission failure. Some factors that may affect this node are: ground safety, ease of operation, and test cell capacity.

- **Back Pressure** -- The value of this node is the amount of back pressure, measured in inches of H_2O , caused by the control technology selected. Back pressure is the major factor for judging test cell control technology acceptability. It is the reason bag houses and scrubbers cannot be used (Canfield, 1995).

The value of the **Engine Performance** node is the product of the values of the **EP Fuel Impact** and **EP EM Impact** divided by 100. The equation for this value is:

$$\text{Engine_Performance} = \text{EP_Fuel Impact} * \text{EP_EM Impact} \div 100$$

A sample calculation for **Engine Performance** is: if the impact of the fuel selected is valued at 95, and the value of the engine modification is valued at 90, then **Engine Performance** is valued at:

$$95 * 90 \div 100 = 85.5$$

This engine performance value reflects the fact that both the fuel selected and the engine modification selected lower the overall performance of the jet engine.

The value of the **Other Operational Considerations** and **Other Testing Factors** nodes is found in a similar manner:

$$\text{Other_Operational_Considerations} = \text{OOC_Fuel Impact} * \text{OOC_EM_Impact} \div 100$$

$$\text{Other_Testing_Factors} = \text{OTF_Fuel_Impact} * \text{OTF_CT_Factors} \div 100$$

$$\text{Test_Performance} = \text{Other_Testing_Factors} * \text{Back_Pressure_Score} \div 100$$

The value of the **Back Pressure Score** is influenced by the value of **Back Pressure**. The **Back Pressure Score** is found using the following equation:

$$\text{Back_Pressure_Score} = \begin{cases} [1 - 0.05 * (\text{Back_Pressure})] * 100 & \text{if } \text{Back_Pressure} < 1 \\ 0 & \text{otherwise} \end{cases}$$

A control technology with **Back Pressure** = 0 would score 100 while a technology with **Back Pressure** = 1 would score 95.

The **Back Pressure Threshold** node has a binary, 0 or 1, value. The purpose of this node is to act as a gate which will prevent a strategy with an excessive amount of back pressure from scoring favorably in the **Operational Impact Score** node. The **Back Pressure Threshold** node is needed because back pressure is a key factor for the acceptance or rejection of a control technology. Development requirements for jet engine test cell control technologies call for less than one inch of back pressure (Canfield, 1995). The expression for **Back Pressure Threshold** is:

$$\text{Back_Pressure_Threshold} = \begin{cases} 1 & \text{if } \text{Back_Pressure} < 1 \\ 0 & \text{otherwise} \end{cases}$$

Operational Impact Score is the final score for the operational impact module. It is a weighted average of the **Engine Performance**, **Other Operational Considerations**, and

Test Performance nodes gated by the **Back Pressure Threshold** node. The weights in this equation are:

- **EP Weight** -- The weight given to the value of **Engine Performance**,
- **OOO Weight** -- The weight given to the value of **Other Operational**

Considerations, and

- **TP Weight** -- The weight given to the value of **Test Performance**.

The equation for the **Operational Impact Score** node is:

$$\text{Operational_Impact_Score} = \text{Back_Pressure_Threshold} * (\text{EP_Weight} * \text{Engine_Performance} + \text{OOO_Weight} * \text{Other_Operational_Considerations} + \text{TP_Weight} * \text{Test_Performance})$$

where;

$$\text{EP Weight} + \text{OOO Weight} + \text{TP Weight} = 1.$$

This completes the description of the relationships contained in the operational impact module which results in an **Environmental Impact Score** for each alternative strategy.

The next module described is the environmental compliance module.

Environmental Compliance. Figure 9 is the influence diagram representing the environmental compliance module. Similar to the operational impact module, the three decisions to be made influence the various value nodes. The **NO_x**, **CO**, **UHC**, **SO₂** and **PM** represent the percent reduction of each pollutant type emission from the level of emissions that would occur if the baseline strategy is used. For example, **NO_x** is the

percent reduction of NO_x emissions for the strategy from the emission levels of the baseline option.

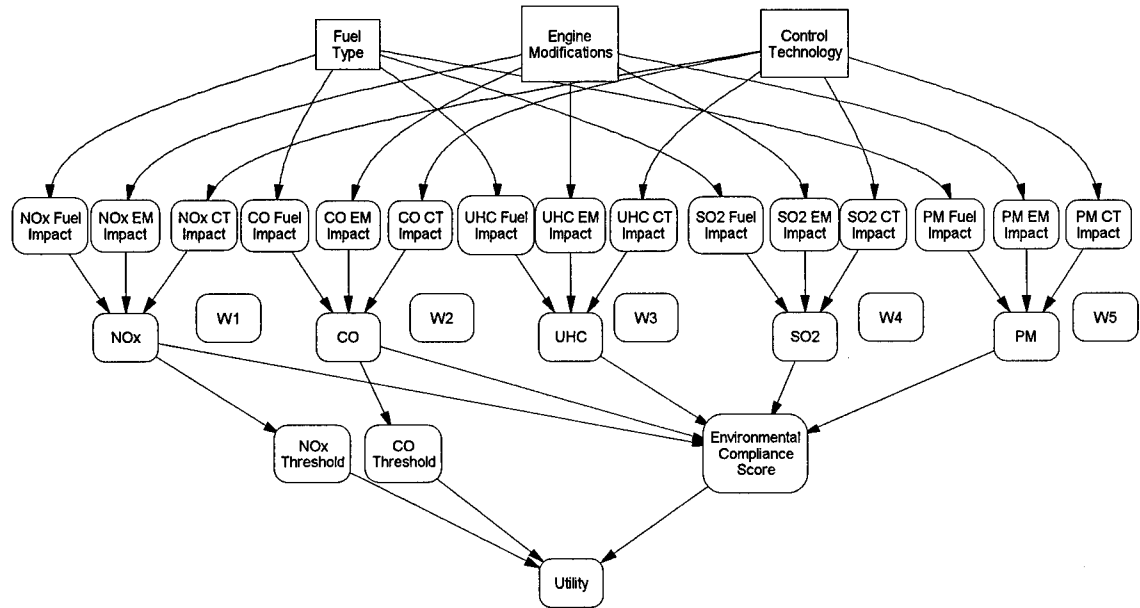


Figure 9 Environmental Compliance Module Influence Diagram

The NO_x node is influenced by three other nodes:

- **NO_x Fuel Impact** -- The percent reduction of NO_x emissions from the baseline because of the fuel type,
- **NO_x EM Impact** -- The percent reduction of NO_x emissions from the baseline because of an engine modification, and
- **NO_x CT Impact** -- The percent reduction of NO_x emissions from the baseline by using a test cell control technology.

The value of **NOx** is the overall percent reduction represented by the previous three nodes. This reduction is found using the following equation:

$$\text{NOx} = 1 - [1 - \text{Nox_Fuel_Impact}] * [1 - \text{Nox_EM_Impact}] * [1 - \text{NOx_CT_Impact}]$$

The values **CO**, **UHC**, **SO2** and **PM** are found in the same manner as **NOx**:

$$\text{CO} = 1 - [1 - \text{CO_Fuel_Impact}] * [1 - \text{CO_EM_Impact}] * [1 - \text{CO_CT_Impact}]$$

$$\text{UHC} = 1 - [1 - \text{UHC_Fuel_Impact}] * [1 - \text{UHC_EM_Impact}] * [1 - \text{UHC_CT_Impact}]$$

$$\text{SO2} = 1 - [1 - \text{SO2_Fuel_Impact}] * [1 - \text{SO2_EM_Impact}] * [1 - \text{SO2_CT_Impact}]$$

$$\text{PM} = 1 - [1 - \text{PM_Fuel_Impact}] * [1 - \text{PM_EM_Impact}] * [1 - \text{PM_CT_Impact}]$$

Environmental Compliance Score is a weighted average of **NOx**, **CO**, **UHC**, **SO2** and **PM**. It is found by the equation:

$$\text{Environmental_Compliance_Score} =$$

$$\text{W1*NOx} + \text{W2*CO} + \text{W3*UHC} + \text{W4*SO2} + \text{W5*PM}$$

Where:

$$\text{W1} + \text{W2} + \text{W3} + \text{W4} + \text{W5} = 1$$

The weights, W_i are used to model the decision maker's preference for which pollutants are the most important to reduce.

Like the **Back Pressure Threshold** node, the **NO_x Threshold** node has a binary, 0 or 1, value. The purpose of this node is to act as a gate which will prevent a strategy with a NO_x reduction unacceptable to the decision maker from having a non-zero environmental **Utility**. This node is needed because NO_x reduction is important and the decision maker does not prefer options that do not reduce NO_x emissions. The 10% reduction threshold is an arbitrary value selected after discussion with the decision makers (Isaacs, 1995). The expression for this node is:

$$\text{NO}_x_Threshold = \begin{cases} 1 & \text{NO}_x < 10\% \\ 0 & \text{NO}_x \geq 10\% \end{cases}$$

The **CO Threshold** node serves the same purpose as the **NO_x Threshold** node except that it is a gate against low CO reduction instead of low NO_x reduction.

Utility is the final score for the environmental compliance module. It is the **Environmental Compliance Score** gated by the threshold nodes. The equation for the **Utility** node is:

$$\text{Utility} = \text{NO}_x_Threshold * \text{CO_Threshold} * \text{Environmental_Compliance_Score}$$

The past two sections have described the operation impact and environmental compliance modules. In the following two sections will describe how the cost and time modules provide additional information to the decision maker about each of the alternative strategies.

Cost. The cost module influence diagram is contained in Figure 10. The influence diagram contains four major cost nodes. Each of these nodes represents a major cost category:

- **R&D Cost** -- The costs incurred during the research and development process needed to develop the strategy,
- **Acquisition Cost** -- The initial capital costs associated with purchasing equipment needed for the strategy,
- **Facility Cost** -- The initial capital costs associated with modifying or constructing facilities to support the strategy, and
- **O&M Cost** -- The change in annual operations and maintenance costs from the baseline costs associated with the strategy.

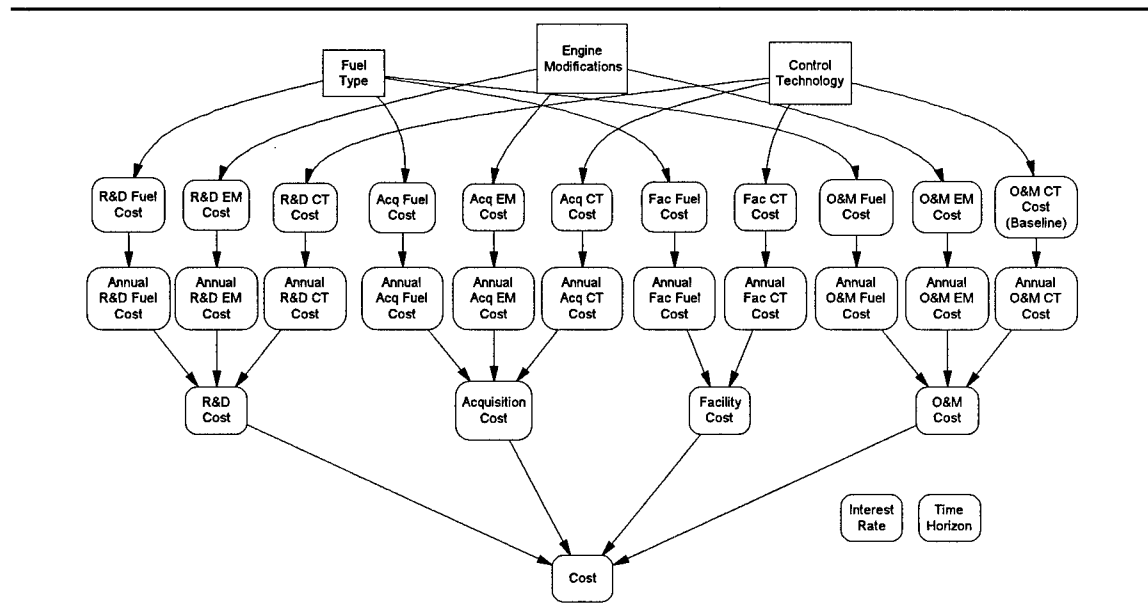


Figure 10 Cost Module Influence Diagram

All these costs are expressed as net present cost (NPC) where costs are positive and savings are negative. The interest rate used for these calculations is 7.9%, which is the 10-year nominal interest rate issued by SAF/FMCE (SAF/FMCE, 1995). **The costs are**

collected through the year 2025. Where O&M Cost is the NPC of the annual O&M cost from the year the technology is implemented until the year 2025.

The value of each of the above four nodes is influenced by the value contained in the three associated annual cost nodes. The calculations for the **R&D Cost** node illustrate how the values for the **R&D Cost**, **Acquisition Cost** and **Facility Cost** nodes are computed. The value of the **R&D Cost** node is the sum of the values in the following nodes:

- **R&D Fuel Cost** -- The research and development costs resulting from the fuel type selected,
- **R&D EM Cost** -- The research and development costs resulting from an engine modification selected, and
- **R&D CT Cost** --The research and development costs resulting from the development of the selected test cell control technology.

These three costs are annualized in the nodes: **Annual R&D Fuel Cost**, **Annual R&D EM Cost** and **Annual R&D CT Cost**. The following conditional equation calculates the value of **Annual R&D Fuel Cost**. The other nodes are calculated using similar equations.

$$\begin{aligned} \text{If } \mathbf{R\&D_Fuel_Time} = 0 \text{ then } \mathbf{Annual_R\&D_Fuel_Cost} &= \mathbf{R\&D_Fuel_Cost}, \\ \text{else } \mathbf{Annual_R\&D_Cost} &= \mathbf{R\&D_Fuel_Cost / R\&D_Fuel} \end{aligned}$$

This equation annualizes the cost of the R&D programs so that the cost of each R&D program is spread across the years during which R&D occurs. Acquisition Cost and

Facility Cost are computed similarly except the implementation time nodes are used for both instead of the R&D time nodes. Even though the influence arcs from the time nodes to these cost nodes is not drawn, it is apparent from the equation that the annual cost nodes are influenced by the value of the time nodes discussed later in the time module section.

The annual O&M cost nodes are calculated differently than the annual R&D, Fuel and Facility nodes. The O&M costs are entered into the **O&M Fuel Cost**, **O&M EM Cost**, and **O&M CT Cost (Baseline)** nodes as annual amounts. The equations used to compute the annual O&M nodes are listed below.

$$\text{Annual_O\&M_Fuel_Cost} = \text{O\&M_Fuel_Cost}$$

$$\text{Annual_O\&M_EM_Cost} = \text{O\&M_EM_Cost}$$

$$\text{Annual_O\&M_CT_Cost} = \text{O\&M_CT_Cost_Baseline} * (1-\text{NOx_Fuel_Impact}) * (1-\text{NOx_EM_Impact})$$

The reason the **Annual O&M CT Cost** is discounted by **NOx Fuel Impact** and **NOx EM Impact** is because the O&M Costs for Control Technologies are collected in terms of dollars per pounds of NO_x removed. If the fuel or engine used reduces the amount of NO_x, then the annual O&M costs will be lower.

The value of the **Cost** node is the sum of the values of the **R&D Cost**, **Acquisition Cost**, **Facility Cost**, and **O&M Cost** nodes. The **Cost** node represents the net present value of the strategy.

Time. The final module of the decision support model is the time module (Figure 11). In this module, the estimated time to field the strategy is computed.

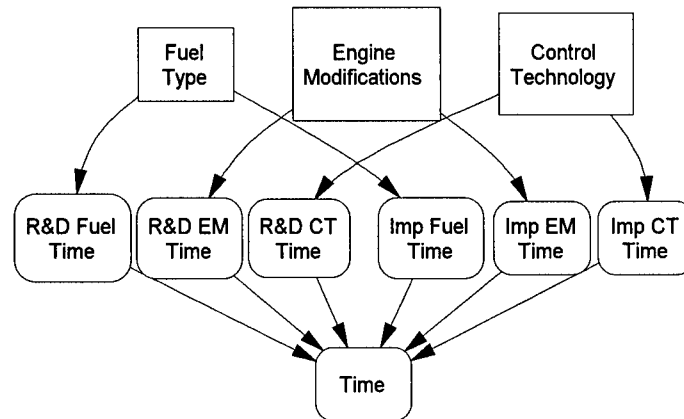


Figure 11 Time Module Influence Diagram

The three decisions influence the value of the six individual time nodes as shown:

- **R&D Fuel Time**, **R&D EM Time** and **R&D CT Time** represent the number of years it will take to research and develop the fuel, engine modification, and jet engine test cell control technology for the alternative strategy selected.

- **Imp Fuel Time**, **Imp EM Time**, and **Imp CT Time** represent the number of years it will take to implement the fuel, engine modification, and jet engine test cell control technology for the alternative strategy selected.

The value of the node **Time** is the number of years it will take to make the strategy operational in the field. This value is found by the following equation:

$$\text{Time} = \text{MAX} (\text{R\&D_Fuel_Time} + \text{Imp\&Fuel_Time}, \\ \text{R\&D_EM_Time} + \text{Imp\&EM_Time},$$

R&D_CT_Time + Imp_CT_Time)

Decision Tree. While the influence diagram is effective at showing the decision maker the influences and relationships within the decision problem, a decision tree is needed to solve the model. At this point in the modeling effort, all the nodes in the model are deterministic. Therefore, the decision tree is quite simple. As Figure 12 shows, it contains only the three decisions. The shorthand decision tree notation used in Figure 7 is described in Appendix A.

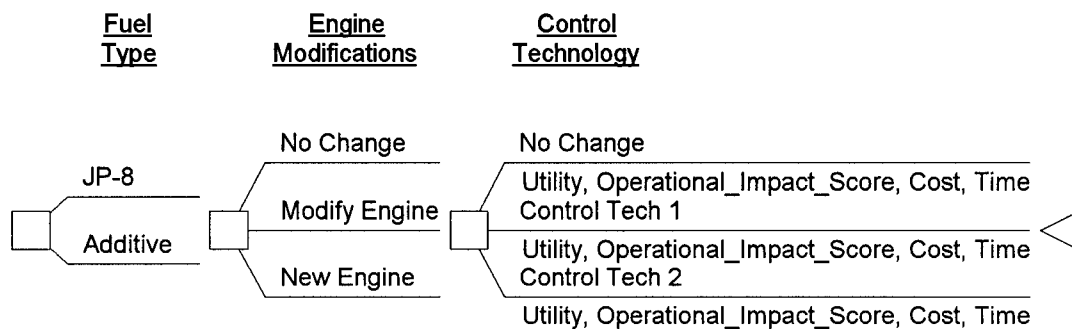


Figure 12 Decision Tree

Step D1. Identify Alternatives. In the previous chapter, the state-of-the-art for aviation fuels, jet engines, and jet engine test cell control technologies was discussed. This research will not directly evaluate the alternatives uncovered during the literature review. Rather, notional alternatives based on these technologies will be evaluated. As research progresses and additional alternatives are defined, the model can be used to evaluate actual alternative decision strategies. The notional decision strategies compared in this research are summarized in a Strategy Generation Table found in Figure 13.

Strategy Generation Table

Strategy	<i>Pre-Process</i>	<i>Within Process</i>	<i>Post-Process</i>
	<i>Fuels</i>	<i>Engine</i>	<i>Control Technology</i>
Baseline Strategy →	JP-8	No Change	No Change
	Additive	Modify Engine New Engine	Control Technology 1 Control Technology 2

Figure 13 Strategy Generation Table

Conceptual Model Summary

Steps One through Four and Steps M1 and D1 complete the development of the conceptual decision model. At this point, the objectives and sub-objectives of the decision maker have been identified, along with the decisions to be made by the decision maker. The decision maker has reviewed the objectives and decisions and concurred that they capture the important aspects of the decision problem. The problem has been modeled using an influence diagram and the feasible alternatives for analysis have been identified and summarized in the strategy generation table. The DPL™ language program for this deterministic model is located in Appendix C.

In the next chapter, data relating to the proposed alternatives are presented and the balance of the steps presented in Figure 5 are completed.

IV. Data Description and Analysis

This chapter will describe the notional data collected and the analysis of this data using the model developed in the previous chapter. The analysis uses preliminary data to uncover those data points that have a value range that can change the preferred alternative. These data points are called key uncertainties.

Identify Key Uncertainties

The first action in this step is to collect point estimates for the value nodes of each of the alternatives. These estimates are entered into the model. By analyzing this deterministic model, the decision analyst can determine which decision is preferred when there is no uncertainty. The data collected for this research is contained in Appendix B. Point estimates are used for the values of the operational impact, cost and time nodes, and the mode is used as a point estimate for each pollutant reduction node.

Step D2. Collect Preliminary Alternative Data. The data used in this chapter is notional. The data is representative of the types of technologies under development. The data is not specific to any of the technologies discussed in Chapter Two. However, the values used for the various alternatives are inspired by those technologies and are within the range of possibilities.

Step M2. Preliminary Sensitivity Analysis. In this step, the model is analyzed deterministically to see what the preferred decision would be if there were no

uncertainties. However, the model contains two weighting schemes which must be set prior to running the analysis. The first is in the operational impact module. During the preliminary sensitivity analysis, the nodes, **EP Weight** (Engine Performance), **OOC Weight** (Other Operational Considerations), and **TP Weight** (Test Performance), are all equally valued at one-third. The second weighting scheme is in the environmental compliance module. These weights are used to compute the **Environmental Compliance Score**. They are valued as follows:

$$W1=2/7, W2=2/7, W3=1/7, W4=1/7 \text{ and } W5=1/7.$$

The weighting scheme was initially selected to put additional weight on the reduction of NO_x and CO. It was then discussed with the decision maker to determine if this set of weights was reasonable (Isaacs, 1995). The significance of the **Environmental Compliance Score** weighting scheme is that it makes the percent reduction of NO_x and CO are twice as significant as the percent reduction of hydrocarbons, SO₂ and particulates. These weight schemes will remain the same throughout the preliminary sensitivity analysis. Later, the significance of these weights and their ability to change the preferred decision will be analyzed.

Table 1 contains the results of the first analysis run. The table shows that the most environmentally beneficial strategy, based on percent reduction of pollutants in the test cell, is to use a fuel additive, a new engine, and control technology 2. However, this is

also the most expensive strategy and does not have as high an **Operational Impact Score** as some of the other options. Clearly, more information is needed before the decision maker can select a strategy given these conflicting attributes.

A series of graphs may provide the decision maker with additional information with which to make a decision. These graphs will plot environmental compliance **Utility vs Time** with the net present costs noted by each alternative. The factor that determines whether an alternative appears on a particular graph is the **Operational Impact Score** of the alternative. An objective of the decision problem is to minimize the negative operational impact of the strategy selected. For this reason, the graphs will show a set of alternatives with a minimum amount of impact. If none of the alternatives shown is acceptable and the decision maker desires more choices, then the decision maker can relax the operational impact requirement.

Table 1 Results of First Deterministic Analysis

Strategy	Environmental Compliance (1.00 best)	Operational Impact (100 best)	Cost (NPV in) (\$Millions)	Time (years)
JP8, No Change, No Cont Tech	0	100	0	0
JP8, No Change, Cont Tech 1	0.436	98.5	0.689	3
JP8, No Change, Cont Tech 2	0.607	98.5	0.608	5
JP8, Modify Engine, No Cont Tech	0	98.7	61.6	9
JP8, Modify Engine, Cont Tech 1	0.492	97.2	62.2	9
JP8, Modify Engine, Cont Tech 2	0.630	97.2	62.2	9
JP8, New Engine, No Cont Tech	0	100	203	6
JP8, New Engine, Cont Tech 1	0.506	98.5	204	6
JP8, New Engine, Cont Tech 2	0.638	98.5	204	6
Additive, No Change, No Cont Tech	0	99.3	5.94	7
Additive, No Change, Cont Tech 1	0.461	97.9	6.62	7
Additive, No Change, Cont Tech 2	0.623	97.8	6.55	7
Additive, Modify Engine, No Cont Tech	0	98	67.5	9
Additive, Modify Engine, Cont Tech 1	0.514	96.6	68.1	9
Additive, Modify Engine, Cont Tech 2	0.645	96.5	68.1	9
Additive, New Engine, No Cont Tech	0	99.3	209	7
Additive, New Engine, Cont Tech 1	0.527	97.9	210	7
Additive, New Engine, Cont Tech 2	0.652	97.8	210	7

Figure 14 contains a graph of the decision strategies that has an operational impact score greater than 98. Using an **Operational Impact Score** of 98 or better results in the four decision strategies with an **Operational Impact Score** of 98.5 being plotted. The alternative strategies are:

- JP8, No Engine Change, Control Technology 1,
- JP8, No Engine Change, Control Technology 2,
- JP8, New Engine, Control Technology 1, and
- JP8, New Engine, Control Technology 2.

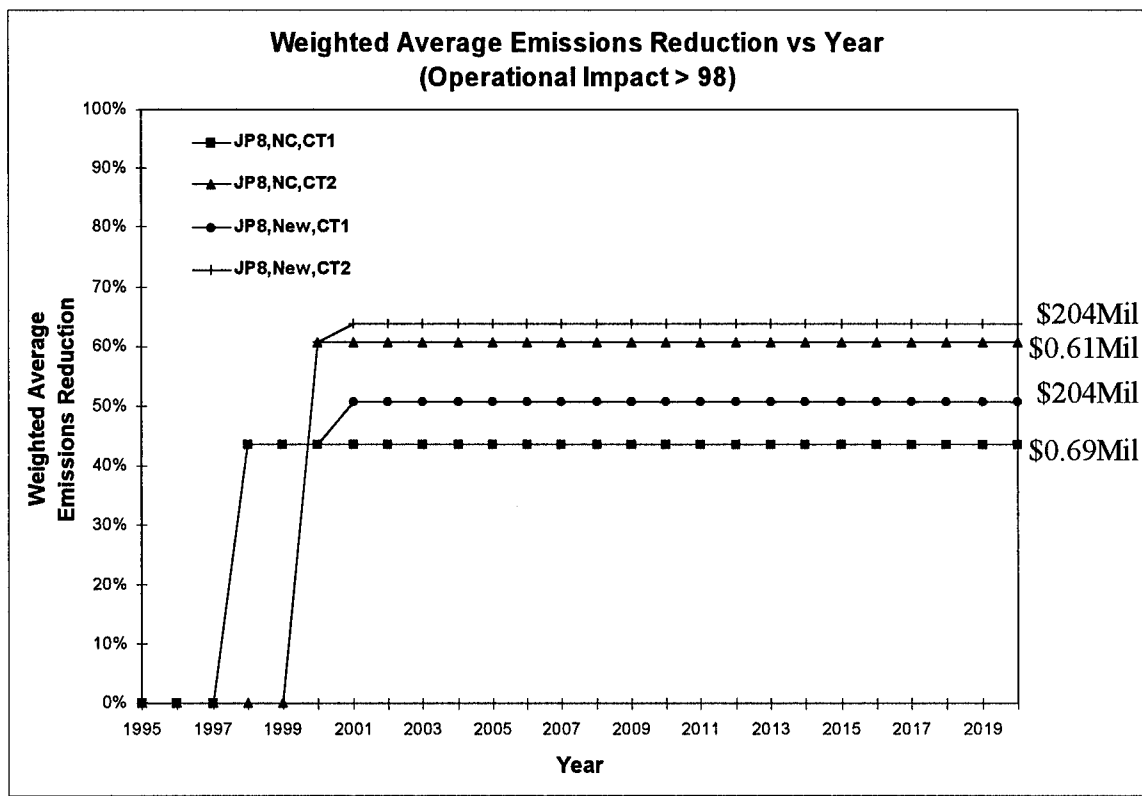


Figure 14 Operational Impact > 98 Strategy Graph

An example of the tradeoffs in this graph: The strategy: JP8, No Change, Control Technology 2 has a higher environmental **Utility** and is lower **Cost** then the JP8, No Change, Control Technology 1. However, it is available later. The decision maker must trade the additional wait vs the lower **Cost** and increased environmental **Utility** to decide to use Control Technology 2 rather than Control Technology 1.

This strategy graph provides the decision maker additional information needed to choose a decision strategy. The purpose of this graph is to present the environmental benefit, cost, and timing of all decision strategies that have an operational impact of at least ninety-eight. If the decision maker desires additional strategy options, these options are

available if the operational impact level is lowered. Figure 15 shows the additional strategies available if the operational impact level is lowered to consider all strategies that have an operational impact greater than 97.5.

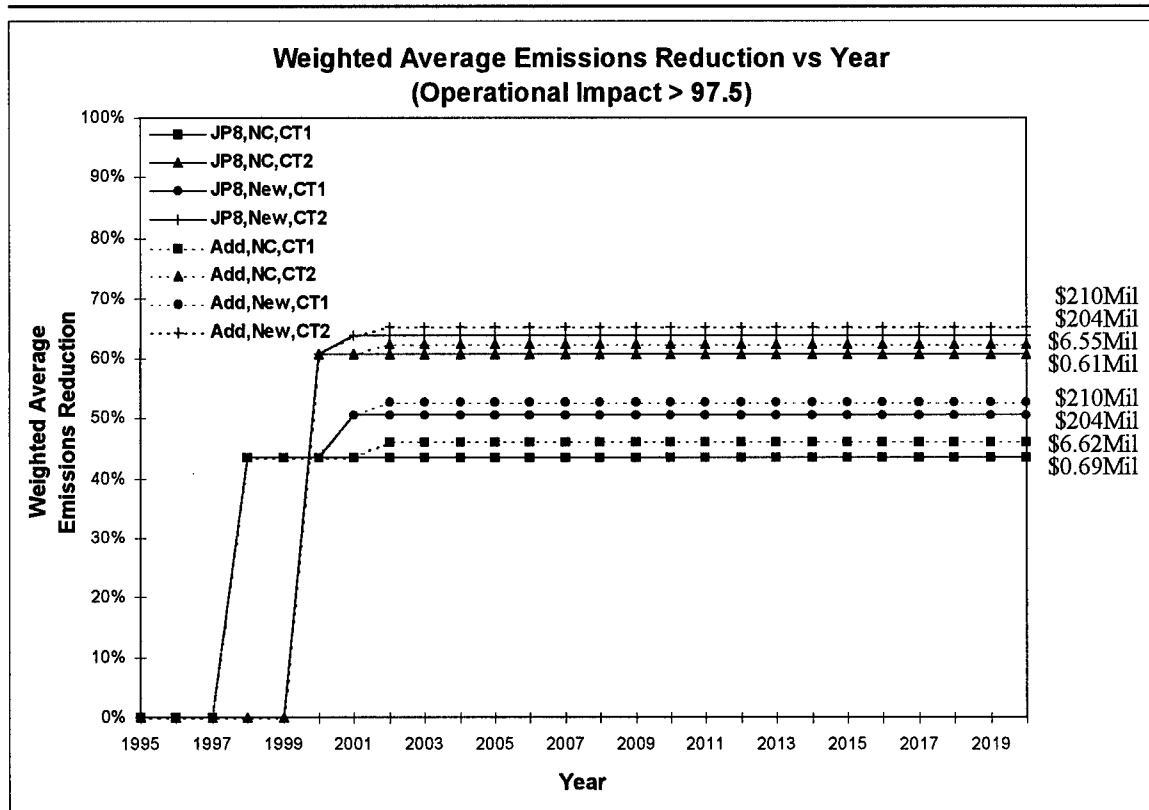


Figure 15 Operational Impact > 97.5 Strategy Graph

This new graph has four additional strategies that the decision maker can consider:

- Additive, No Engine Change, Control Technology 1,
- Additive, No Engine Change, Control Technology 2,
- Additive, New Engine, Control Technology 1, and
- Additive, New Engine, Control Technology 2.

Figure 16 shows that continuing to lower the operational impact provides the decision maker even more choices. The lower the operational impact score the decision maker considers, the less significant the operational impact score becomes to the decision process.

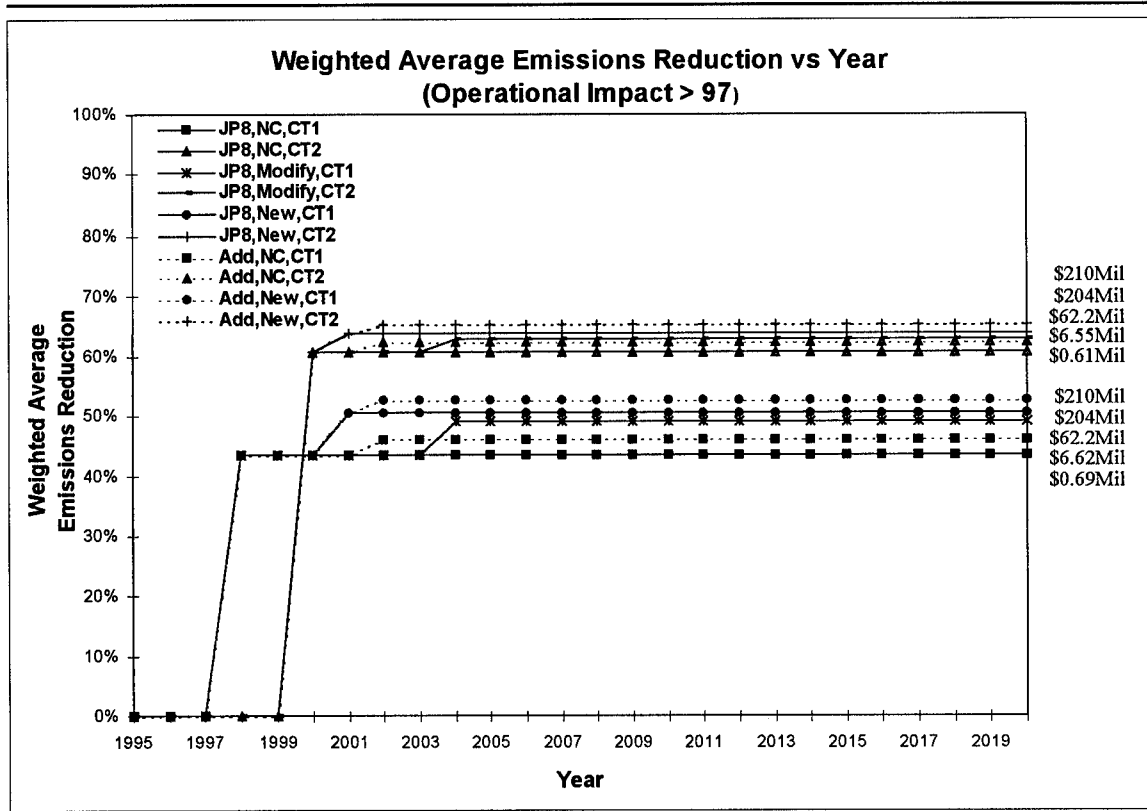


Figure 16 Operational Impact > 97 Strategy Graph

Figures 14, 15 and 16 are effective in presenting the decision maker with the four attributes of the decision problem. However, uncertainty within the data means that additional analysis is required. The next phase of the analysis process will use tornado diagrams to expose the key uncertainties in the model.

Air Combat Command does not want environmental activities to impact the flying mission (Isaacs, 1995). For this reason, this research will limit the data analysis to those strategies

that have a small operational impact. The strategies that will be analyzed all have an operational impact score greater than ninety-eight (100 is no impact). If additional strategies with lower operational impact scores were to be considered, the analysis for those strategies would proceed in the same manner as the analysis in this chapter.

If all of the decision attributes were weight against one another, the process of determining key uncertainties would be simplified. Because this model treats the four attributes individually, the sensitivity analysis is more complex. Table 2 contains the values for each of the attributes for the four strategies.

Table 2 Attributes for Strategies with Operational Impact > 98

Strategy	Environmental Compliance (1.00 best)	Operational Impact (100 best)	Cost (NPV in) (\$Millions)	Time (years)
JP8, No Change, Cont Tech 1	0.436	98.5	0.631	3
JP8, No Change, Cont Tech 2	0.607	98.5	0.580	5
JP8, New Engine, Cont Tech 1	0.506	98.5	204	6
JP8, New Engine, Cont Tech 2	0.638	98.5	204	6

Because the **Operational Impact Score** is used strictly to determine whether a particular strategy will or will not appear on a strategy graph, the score will not be analyzed for uncertainty. If the decision maker desires additional options, another graph can be created using a lower **Operational Impact Score**.

The first attribute analyzed is environmental compliance. This attribute is measured in terms of a weighted average percent reduction in overall emissions. Because the value of the **Utility** node does not determine the preferred decision alone, each strategy with an

operational impact score greater than ninety-eight must be analyzed using a tornado diagram to see if its **Utility** exceeds the strategy above it in Figure 14 or drops below the strategy below it. For a brief explanation of tornado diagrams refer to Appendix A.

Figure 17 contains the tornado diagram for the strategy JP8, New Engine, Control Technology 2. A tornado diagram, or value sensitivity analysis, "calculates the changes in output value . . . as one particular value in the model changes" (ADA, 1995:474). The tornado diagram is ordered from top to bottom with the model value that has the greatest range of output values on top and the model value with the least on the bottom. The numbers under each end of the sensitivity bar indicate the model value / the output value.

For example, the top sensitivity bar in Figure 17 represents the fact that if Control Technology 2 (pulsed plasma) is selected, the value of **CO CT Impact** can range from 0.4 to 0.65. This has the effect of varying the environmental compliance **Utility** from 0.661 to 0.679 for the decision strategy JP8, New Engine, Control Technology 2. Table 2 shows that this strategy has the highest environmental compliance **Utility**. If the range had caused the output value, environmental compliance **Utility**, to drop below 0.607 (the **Utility** for JP8, No Change, Control Technology 2) then the value would need to be modeled probabilistically. In this case, it does not and the point estimate for the effect of Control Technology 2 on **CO CT Impact** can be used in the final analysis. However, if another tornado diagram for a different alternative strategy requires that a value be modeled probabilistically, then the value must be modeled using probability. A point

estimate will only be used if all sensitivity analyses show that the value can be modeled as a point estimate.

Because no value in Figure 17 drops below 0.607, no nodes have the ability to change the order of the alternative strategies based on environmental compliance **Utility**. This diagram does not require any nodes to be modeled as uncertainties. This and all other tornado diagrams in this chapter are generated using a control node model that allows the analyst to specify each decision and thereby analyze each strategy separately. The DPL™ language program that allows this control over the decisions is found in Appendix D.

The tornado diagram for strategy JP8, No Change, Control Technology 1 is contained in Figure 18. This diagram shows that the node **CO CT Impact** should be modeled using uncertainty because it can drive the **Utility** node of this strategy above 0.638 which is the **Utility** of the strategy JP8, New Engine, Control Technology 2.

Figures 19 and 20 do not show any nodes that need to be modeled using uncertainty. The tornado diagram for strategy JP8, New Engine, Control Technology 1 is shown in Figure 19. No nodes cause **Utility** to exceed the **Utility** of the strategy above or to fall below the **Utility** of the strategy below JP8, New Engine, Control Technology 1. Figure 20 shows a similar situation for JP8, No Change, Control Technology 1.

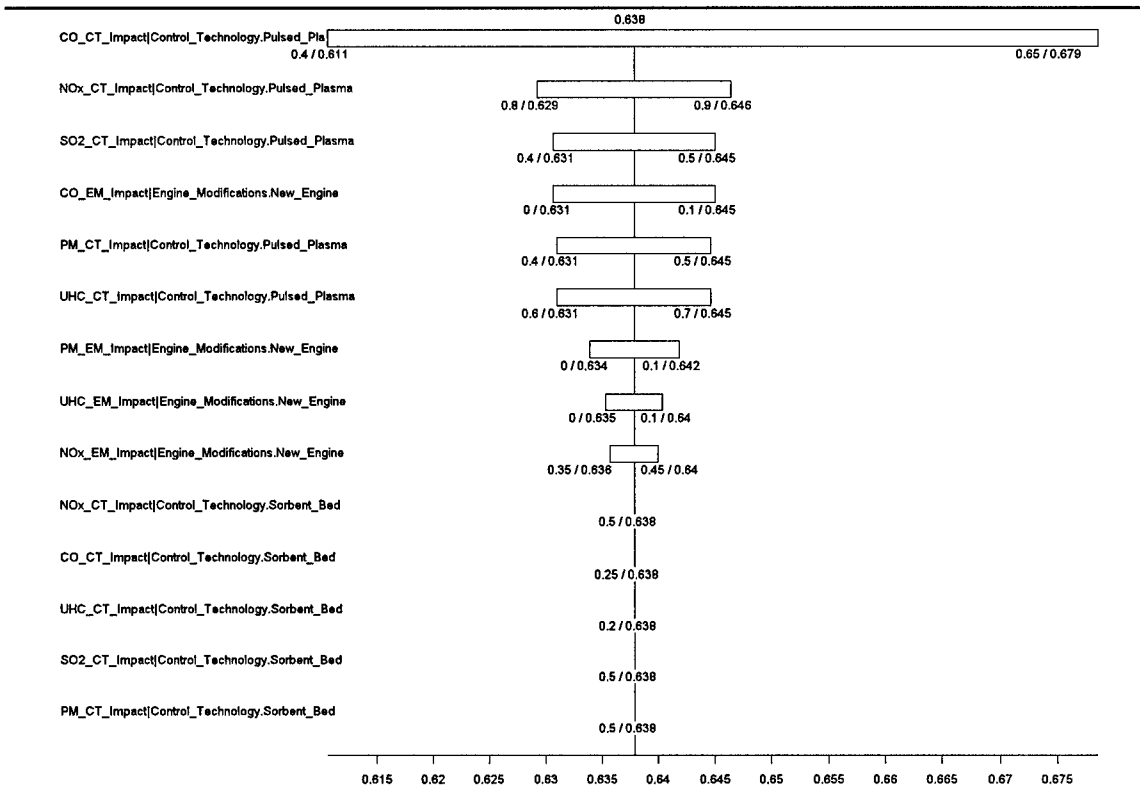


Figure 17 EC Tornado Diagram for JP8, New Engine, CT2

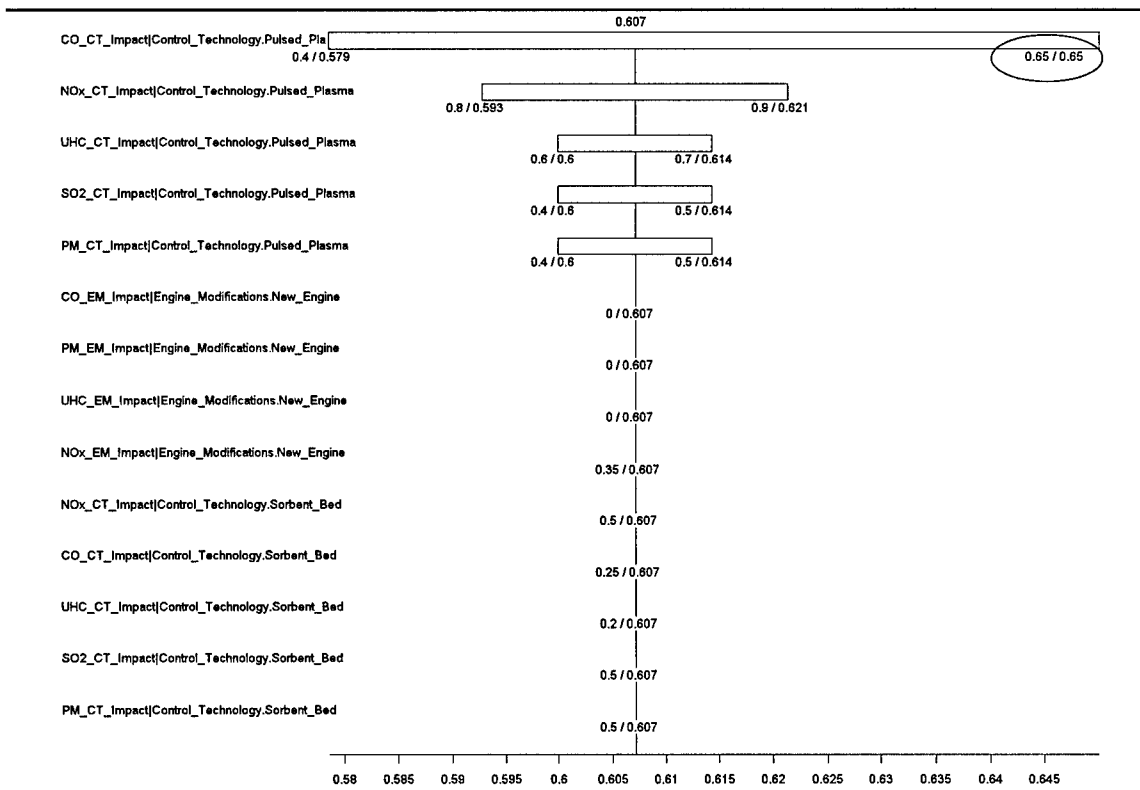


Figure 18 EC Tornado Diagram for JP8, No Change, CT1

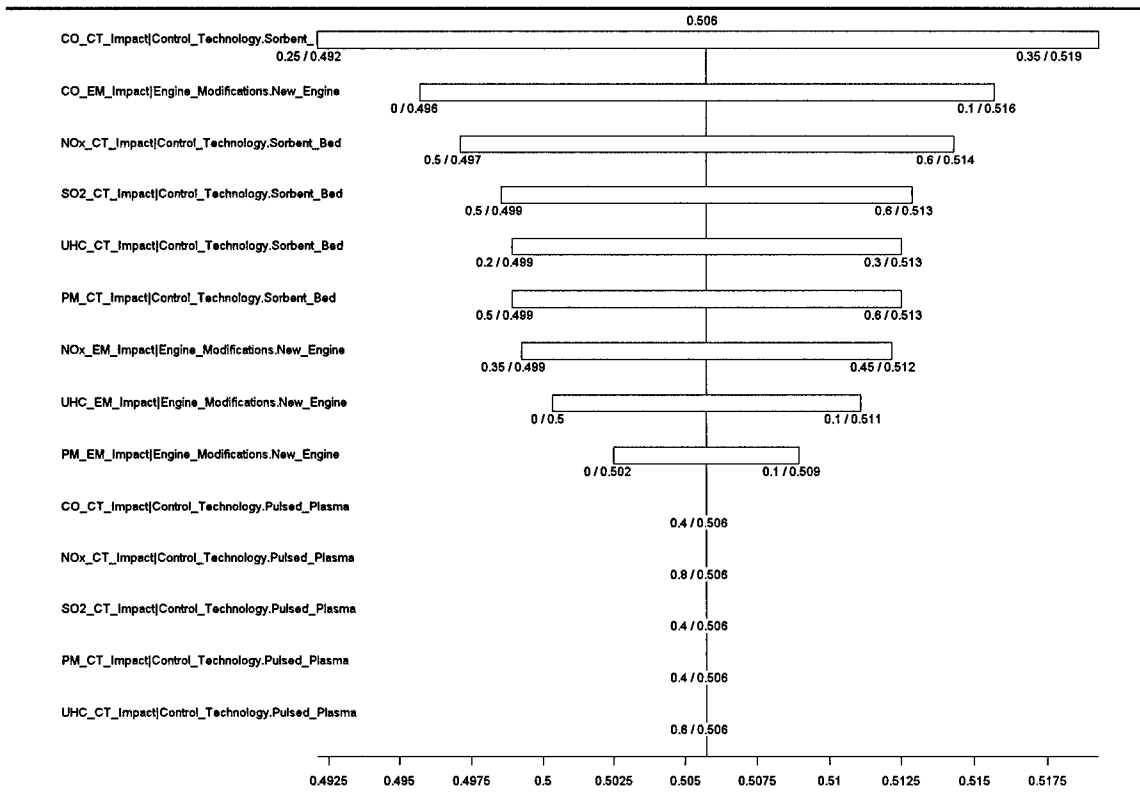


Figure 19 EC Tornado Diagram for JP8, New Engine CT 1

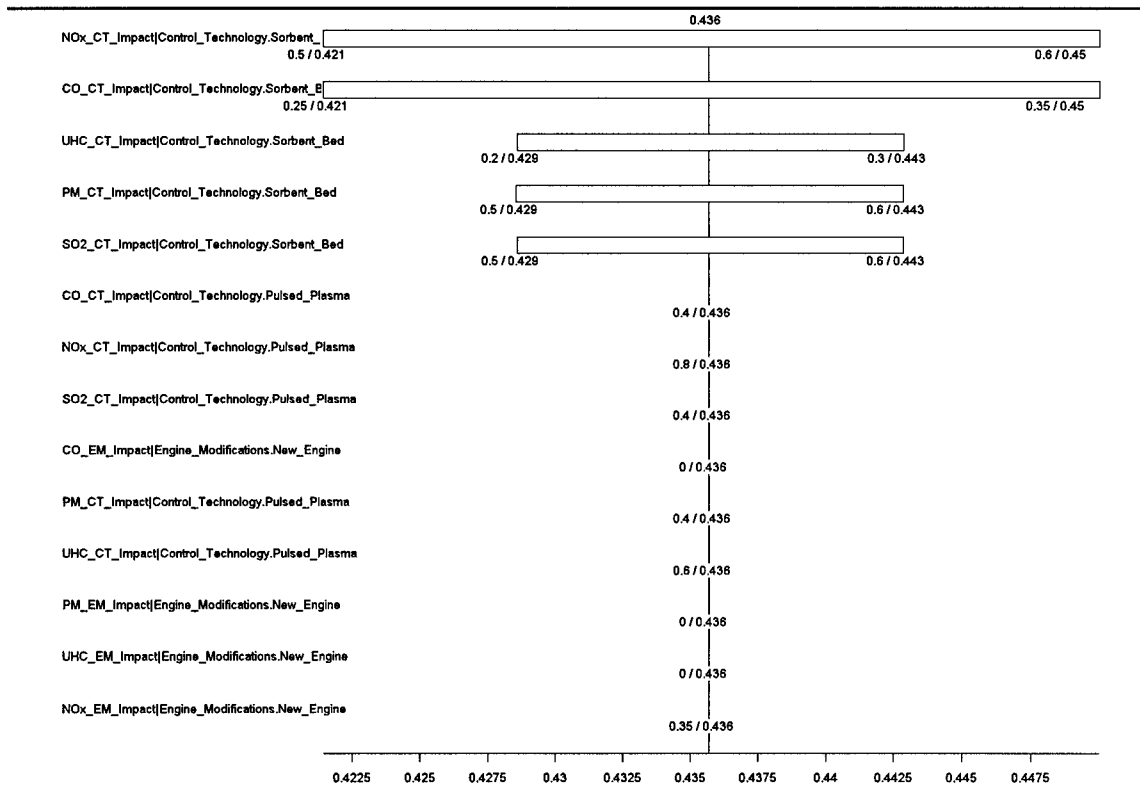


Figure 20 EC Tornado Diagram for JP8, No Change, CT1

The tornado diagrams shown in Figures 17, 18, 19 and 20 indicate that the only node in the environmental compliance module that needs to be modeled using uncertainty is the **CO CT Impact** node. The modeling of this node will be discussed later.

The next module analyzed is the cost module. The first strategy examined is JP8, No Change, Control Technology 2. The tornado diagram (Figure 21) shows that **R&D CT Cost** should be modeled using uncertainty because it can cause the cost to exceed \$0.69 Million which is the cost for strategy JP8, No Change, Control Technology 1.

Figure 22, the tornado diagram for strategy JP8, No Change, Control Technology 1 shows that **O&M CT Cost (Baseline)** should also be modeled using uncertainty because it can cause **Cost** to dip below \$0.61 Million. Figure 23 and 24 both show that **Acq EM Cost** and **R&D EM Cost** should be modeled using uncertainty because JP8, New Engine, Control Technology 2 and JP8, New Engine, Control Technology 1 are both \$204 Million. The smallest change in price will change the preference.

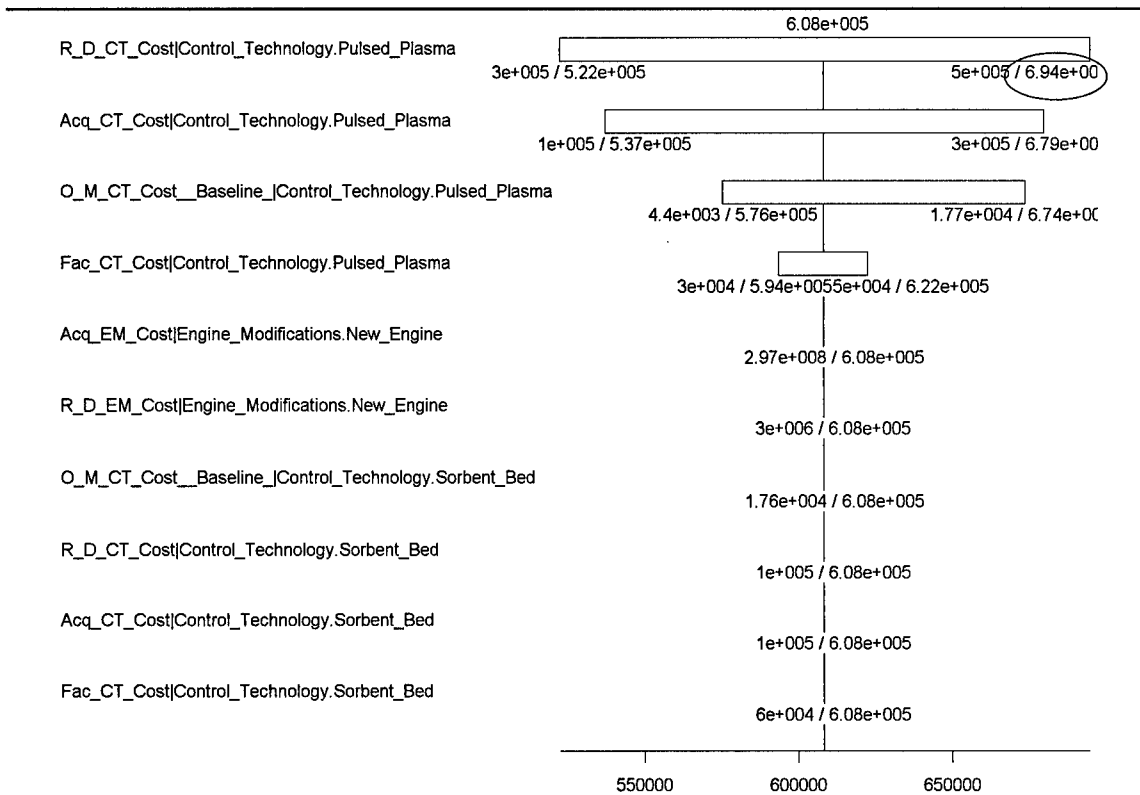


Figure 21 Cost Tornado Diagram for JP8, No Change, CT2

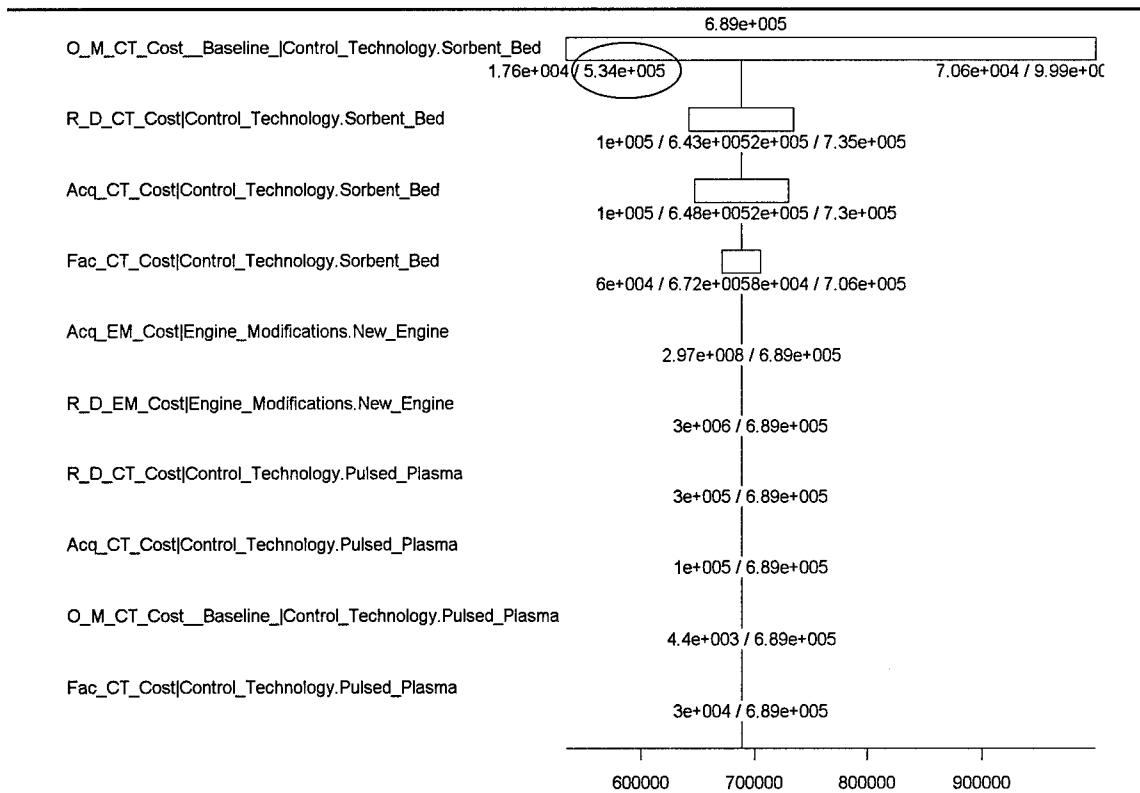


Figure 22 Cost Tornado Diagram for JP8, No Change, CT1

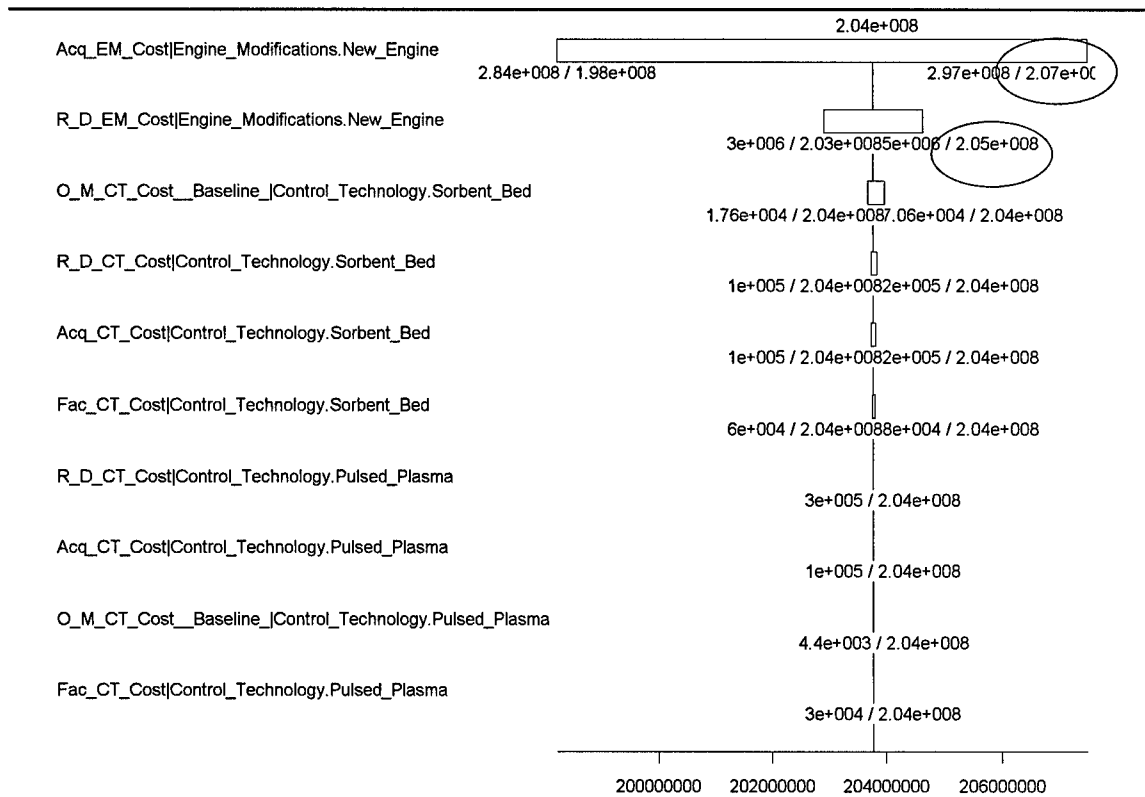


Figure 23 Cost Tornado Diagram for JP8, New Engine, CT2

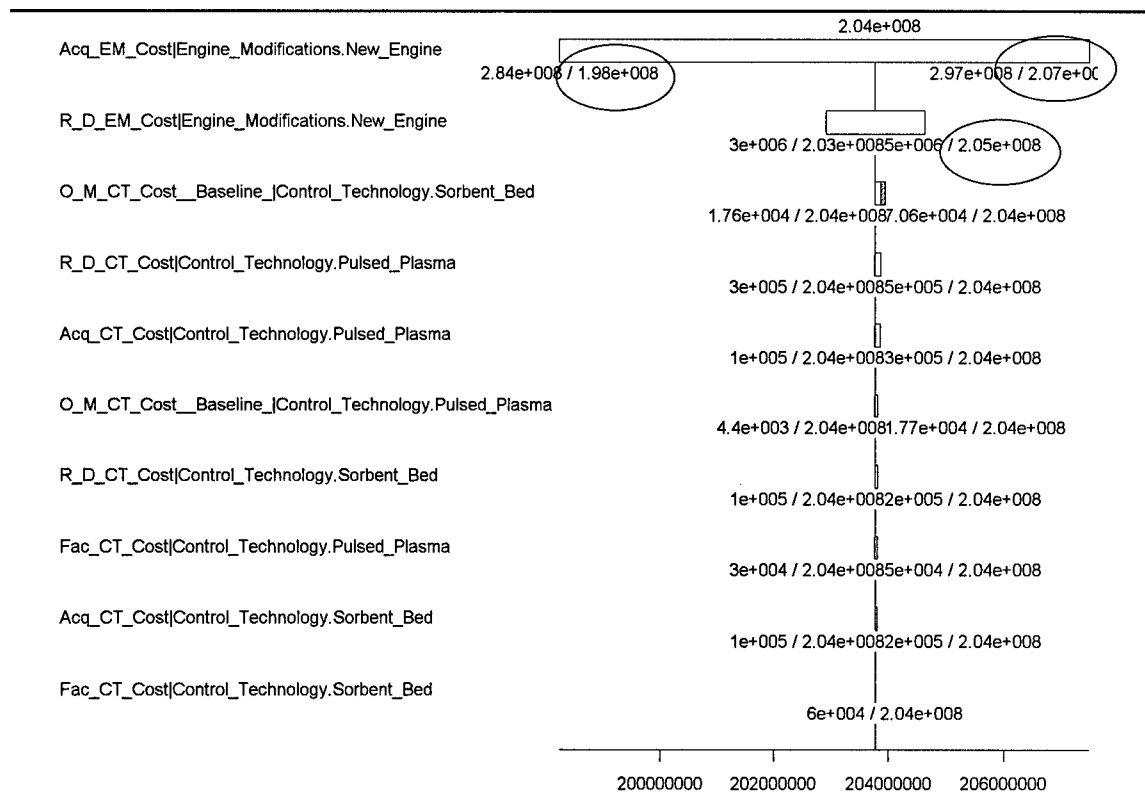


Figure 24 Cost Tornado Diagram for JP8, New Engine, CT1

In addition to the environmental compliance and cost modules, the time nodes were also analyzed for their sensitivity to the range of values. Figures 25, 26, 27 and 28 contain the tornado diagrams for these nodes. No time nodes need to be modeled using uncertainty because none of the nodes could cause a change in the time sequence of the four alternative strategies.

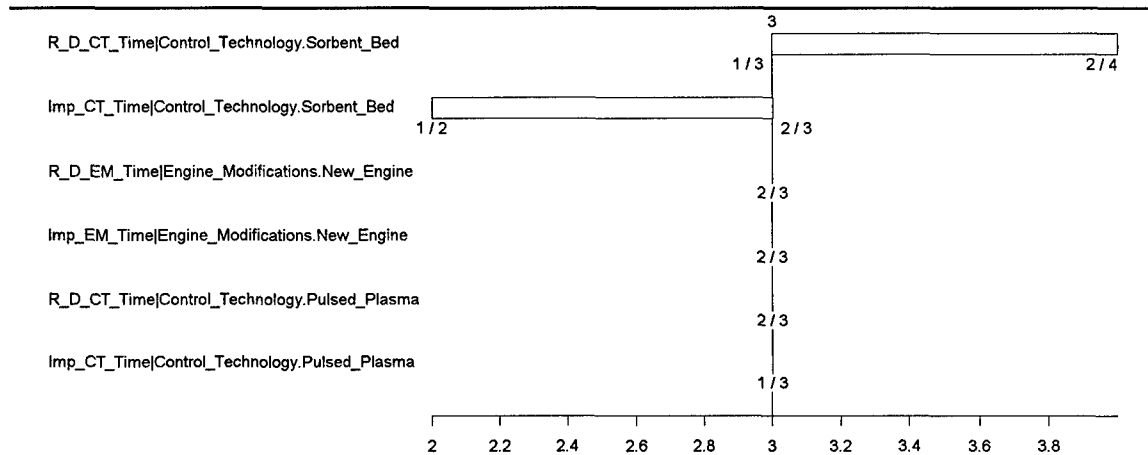


Figure 25 Time Tornado Diagram for JP8, No Change, CT1

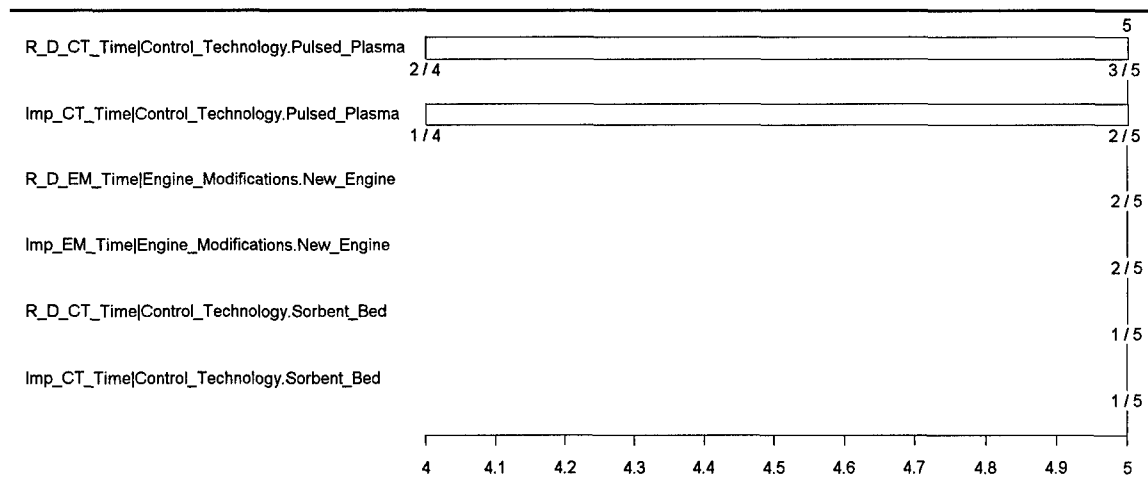


Figure 26 Time Tornado Diagram for JP8, No Change, CT2

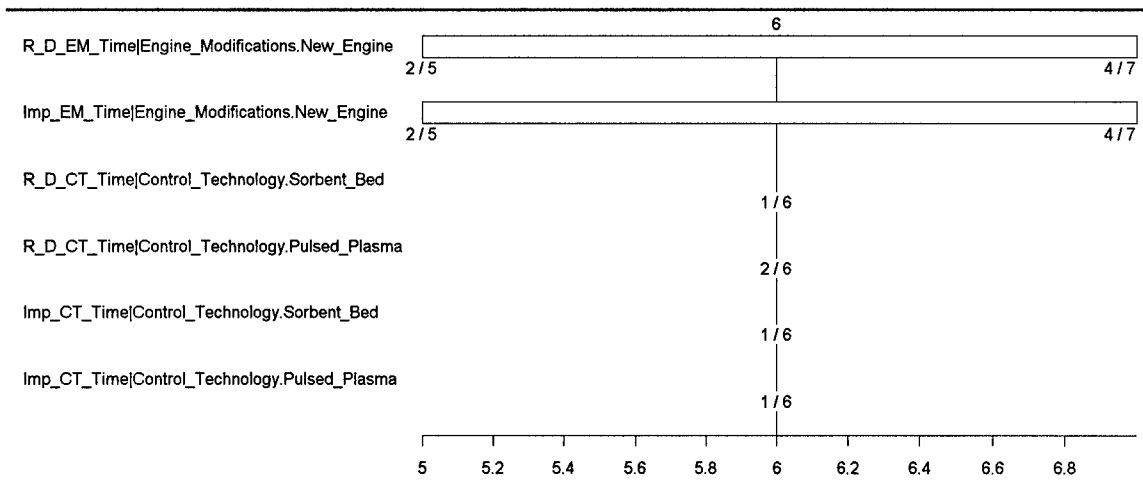


Figure 28 Time Tornado Diagram for JP8, New Engine, CT2

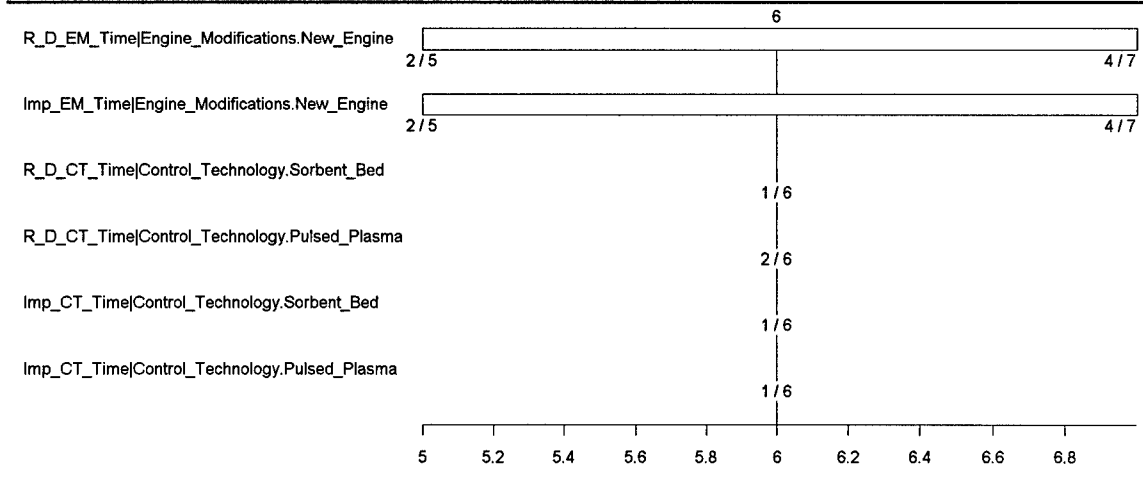


Figure 27 Time Tornado Diagram for JP8, New Engine, CT2

Figure 29 shows that the first four alternatives almost dominate the second four alternatives in all cases where **Test Performance** does not receive 100% of the weight. In fact, the first two alternatives do dominate all the others. For this reason, even in the case of a very large **TP Weight**, the first two alternatives remain in the top four. Changing the weights will change the **Operational Impact Score** for the various alternatives.

However, the **Operational Impact Score** is only used to determine if an alternative

appears on the graph or not. If the decision maker wants at least four alternatives, the same four would appear. They would just have a lower **Operational Impact Score**.

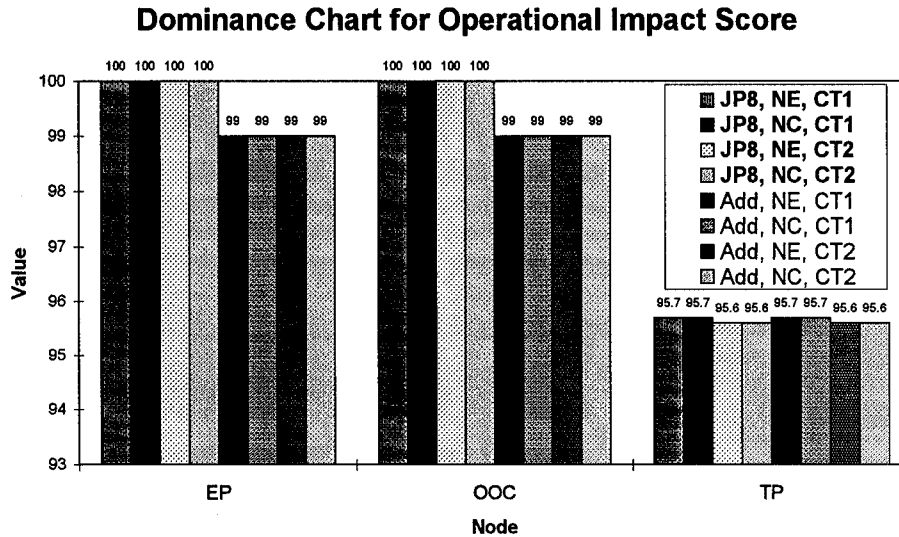


Figure 29 Dominance Chart for Operational Impact Score

Because membership in the list of top four alternatives, based on Operational Impact Score, is not significantly dynamic with changing weights. The weights will be held constant at:

$$\text{EP Weight} = \text{OOC Weight} = \text{TP Weight} = 1/3.$$

Unfortunately, the weights in the environmental compliance module are not as straight-forward. Figure 30 shows that near-dominance relationship seen in the **Operational Compliance Score** weights is not present. To help the decision maker better understand the significance of the weights: **W1, W2, W3, W4** and **W5**, additional sensitivity analysis is needed.

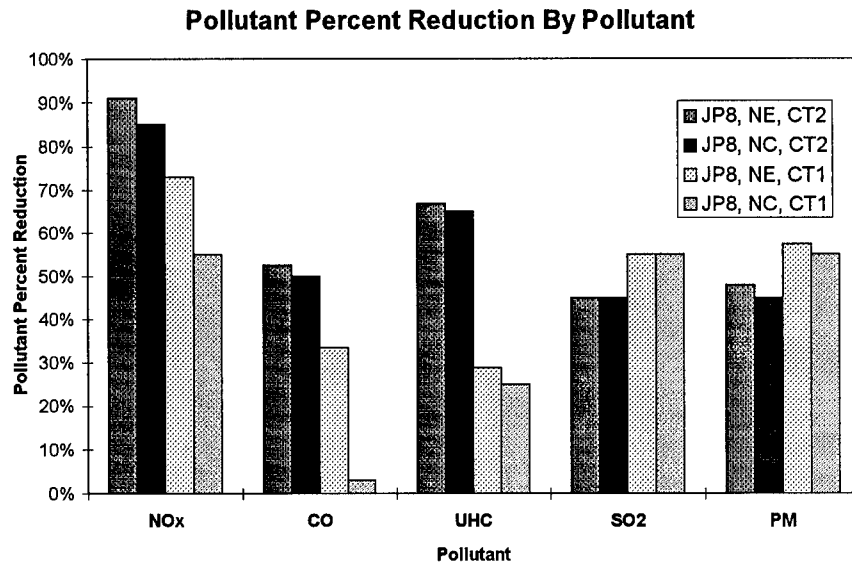


Figure 30 Pollutant Percent Reduction By Pollutant

This sensitivity analysis is accomplished using rainbow diagrams. These rainbow diagrams (Figure 31) are created by varying one weight at a time from zero to one. The other weights are equally set to:

$$\frac{(1 - \text{Weight Varied})}{4}$$

These rainbow diagrams show that unless the value **SO2** or **PM** represents more than 60% of the decision maker's concern, then the strategy with the greatest weighted average percent reduction remains: JP8, New Engine, Control Technology 2. This is significant because it shows that the decision is not very sensitive to the weight scheme. Especially in light of the fact that the initial weight values were:

$$W_1=2/7, W_2=2/7, W_3=1/7, W_4=1/7 \text{ and } W_5=1/7.$$

Where **W1**, **W2**, **W3**, **W4** and **W5** are the weights associated with **NOX**, **CO**, **UHC**, **SO2**, and **PM** respectively.

The fact that **NO_x** and **CO** are weighted twice as heavily as **UHC**, **SO₂** and **PM** means the reduction of either **NO_x** or **CO** is twice as important to the decision maker as reducing any one of the other pollutants.

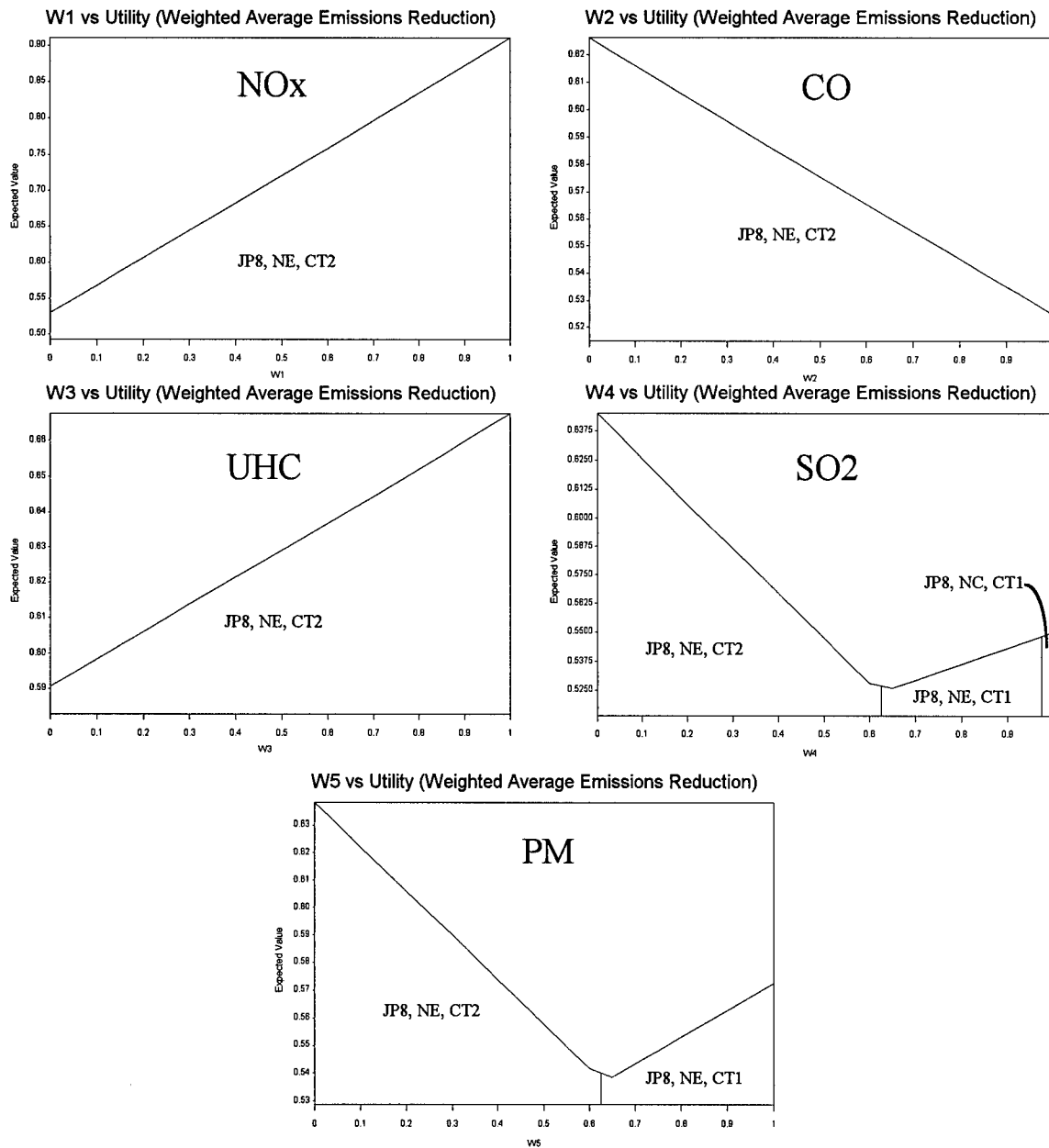


Figure 31 Rainbow Diagrams for Environmental Compliance Weights

Step M3. Model the Key Uncertainties. Now that the key uncertainties have been identified, the analyst must model these values by converting the value nodes to chance nodes in the influence diagram and decision trees. Fortunately, DPL will take care of the decision tree if the influence diagram is changed. The nodes uncovered by the sensitivity analysis that need to be modeled using chance nodes are:

- **CO CT Impact**
- **R&D CT Cost**
- **R&D EM Cost**
- **Acq EM Cost**
- **O&M CT Cost (Baseline)**

These nodes are in the environmental compliance and cost modules. The updated versions of these modules are contained in Figures 32 and 33 respectively. The elliptical nodes are the chance nodes. Now that the model contains chance nodes, the decision tree has changed. The new decision tree, with the chance nodes included, is found in Figure 34.

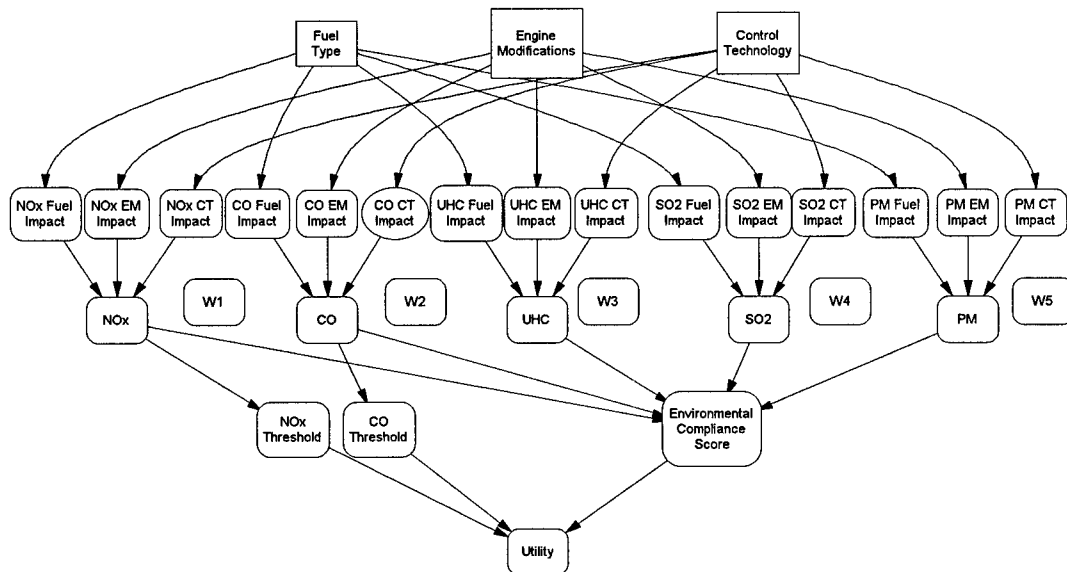


Figure 32 Environmental Compliance Module With Chance Nodes

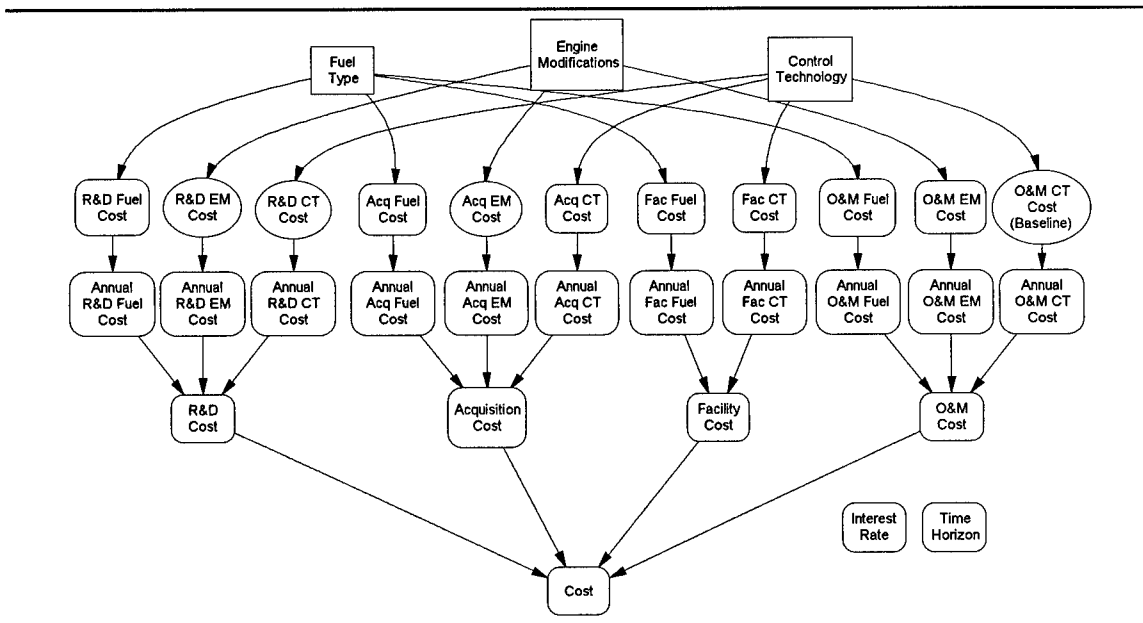


Figure 33 Cost Module with Chance Nodes

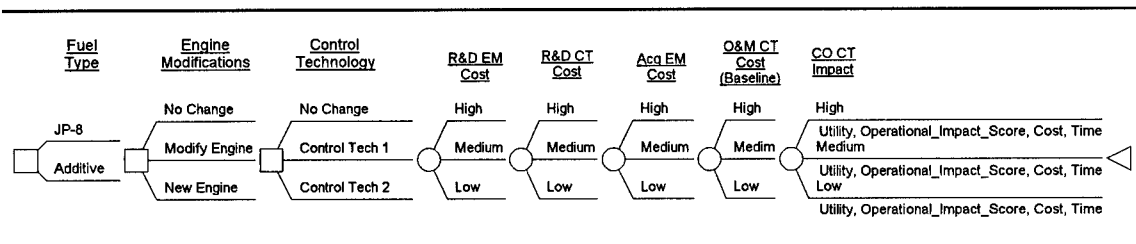


Figure 34 Decision Tree with Chance Nodes

Step M4. Model the Decision Maker's Preference Structure. At this point the decision maker must be consulted about his or her preference structure. The rainbow diagrams from Step M2 should help the analyst explain to the decision maker the sensitivity of the weights.

Because the sensitivity analysis did not show any significant reaction to changes in the weighting schemes, the original weighting schemes that were described earlier will be preserved for the final analysis.

Data Analysis

Step D3. Collect Final Alternative Data. After the needed chance nodes and the decision makers preferences are identified, the final data must be collected. This data gathering should focus on the uncertainties. The data for these notional alternatives is found in Appendix B. The point estimates were used in the preliminary sensitivity analysis. The entire ranges of values will now be used for the chance nodes

These uncertain values must be modeled using probability distributions. The probability distribution used in this research is the triangular distribution. Figure 35 shows a generic triangular distribution. The advantage of this distribution is that it is defined by three values: the minimum possible value, the maximum possible value, and the most likely, or mode, value. This simple distribution allows expert opinion to be easily included in the model. The expert needs to answer three simple questions to develop this distribution.

- What is the minimum value?
- What is the maximum value?, and
- What is the most likely value?

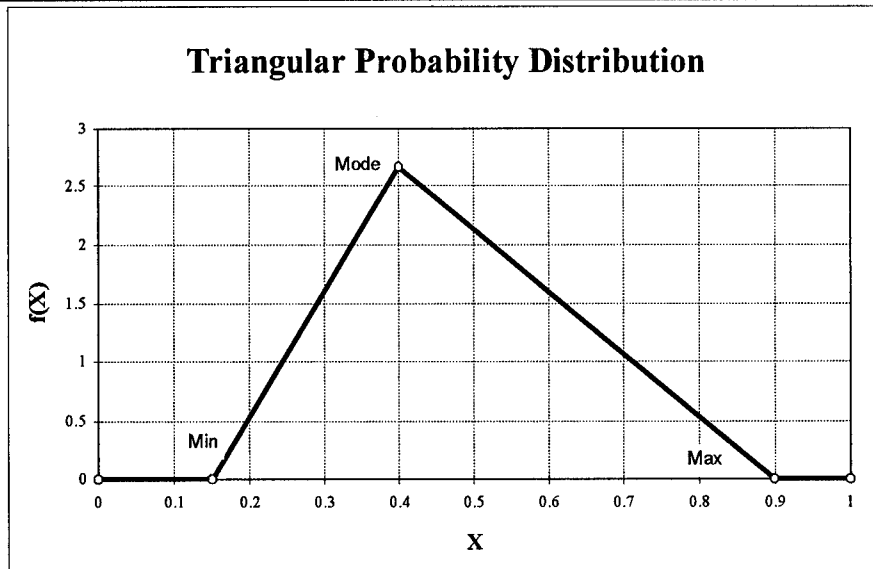


Figure 35 Generic Triangular Probability Distribution

Step 5. Perform Sensitivity Analysis. With the final data collected, sensitivity analysis is again performed. For this sensitivity analysis, probability cumulative distribution functions (CDF) are used to determine if deterministic or stochastic dominance is present. Deterministic dominance means that the value of strategy A will always be greater than the value of strategy B. Stochastic dominance means that the probability that the value of strategy A is greater than the value of strategy B is greater than the probability that the value of strategy B is greater than the value of strategy A.

An example of deterministic dominance is found in Figure 36. The value of strategy JP8, New Engine, Control Technology 1 will always be greater than the value of strategy JP8, No Change, Control Technology 1.

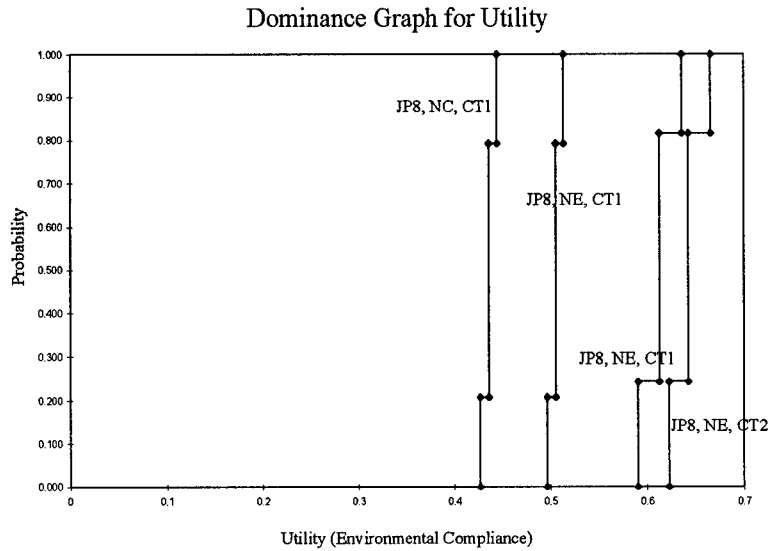


Figure 36 Dominance Graph for Environmental Compliance Utility

An example of stochastic dominance is found in Figure 37. The CDF for strategy JP8, No Change, Control Technology 1 is always to the left of the CDF for strategy JP8, No Change, Control Technology 2. This means that the first strategy stochastically dominates the second. If dominance exists throughout the alternative strategies, then the uncertainty within the model will not affect the preference order of the decisions.

Figure 36 contains the CDF for **Utility**. None of the CDFs for the four alternative strategies cross. This means that there is stochastic dominance throughout. Figure 37 shows a pair of CDF graphs for **Cost**. These functions do not intersect. Therefore, **Cost** has stochastic dominance among all the alternatives also. Since none of the uncertainties in the model has the ability to change the preference order of the alternative, the decisions can be made based on the point estimates for each value in the model.

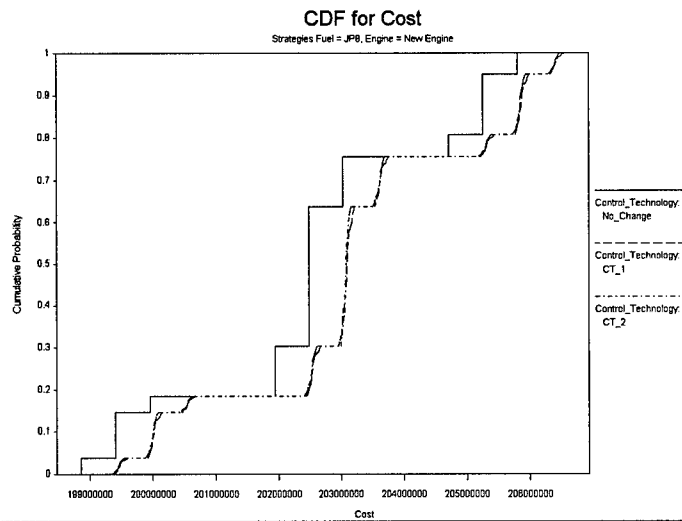
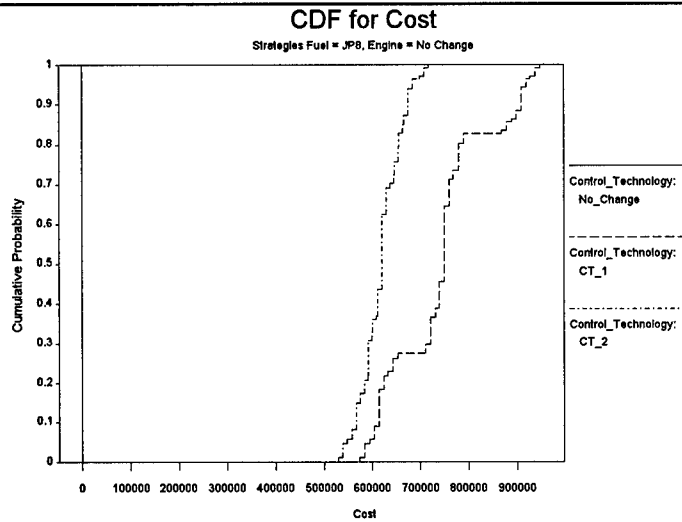


Figure 37 Dominance Graph for Cost

Step 6. Present Preliminary Results. Now that all the analysis is done, the analyst should present his preliminary results to the decision maker. This ensures that all important issues are analyzed. Also, if the decision maker needs additional information before making a decision, this can also be identified.

Problem Check

Step 7. Have the Objectives Been Met. Mr. Larry Isaacs and Ms. Mary Ruth Senn from the Headquarters Air Combat Command Environmental Compliance Office were briefed on the final model and preliminary results on Thursday 9 November 1995.

Step 8. Present Final Results. The final results of this research are presented in Chapter Five.

V. Conclusions

Overview.

This research used decision analysis to provide insight into the question: *How can Air Combat Command efficiently test its jet engines, comply with the environmental requirements of the Clean Air Act as amended in 1990, and maintain operational effectiveness?* To answer this general question, the research goals of this study were to:

1. *Perform a review of modern jet engines and the emissions that result from jet engine testing.* This review focused on the underlying causes of emissions and potential methods to reduce these emissions.

2. *Construct a decision model to compare the various existing and potential strategies for meeting Clean Air Act regulatory requirements during jet engine testing in ACC.*

This model focused on four major objectives:

- Minimize negative operational impact,
- Maximize the environmental benefits,
- Minimize the cost of the strategy, and
- Identify the time it will take to field the strategy.

3. *Use this model to compare the costs and benefits of various notional methods for meeting regulatory requirements by reducing emissions during the testing of Air Combat Command's jet engines.* These notional methods were based on the technologies

uncovered while accomplishing the first goal. The potential of these strategies to reduce emissions from the F110 engine was identified. Block 50 and Block 52 F-16 fighter aircraft use the F110 engine.

Summary of Findings.

State-of-the-Art-Review. Air pollution is a major concern in the United States. Since the creation of the United States, laws regulating the emissions of pollutants have become ever more strict. The Clean Air Act Amendments of 1990 (CAAA) are the latest additions to the growing body of laws, rules and regulations. The regulations resulting from the CAAA have requirements to significantly reduce the amount of air toxics released into the ambient air. The Environmental Protection Agency (EPA) now categorizes jet engine testing as a major air pollution source. Consequently, the CAAA and their regulations have the potential to affect the Air Force's jet engine testing program severely. At some installations in Air Combat Command, the CAAA have already affected the installation's ability to permit new testing facilities.

Many potential solutions exist or are under development that could help the Air Force reduce emissions during jet engine testing. These solutions include new fuels, improved jet engine technology, and jet engine test cell emissions control technology. The specifics of each of these technologies are discussed in the literature review in Chapter Two. Each of these solutions is viewed as having four common attributes:

- An operational impact
- An environmental benefit

- A cost, and
- A lead-time until it can be implemented.

Model Development. This research provides a decision support model to aid Air Combat Command and Air Force decision makers in determining which of these technologies to pursue. This approach is in line with Air Force Doctrine Document 42 that states that Civil Engineers “should provide decision makers with balanced, objective analysis of the true impacts and costs of alternatives for Air Force operations in meeting environmental goals” (DAF, 1994:2.7). The decision support model was created using DPL™ and the decision analysis techniques described in *Making Hard Decisions: An Introduction to Decision Analysis* by Robert T. Clemen and those techniques taught by the faculty of the Operational Sciences Department of the School of Engineering at the Air Force Institute of Technology.

The decision support model was created by looking at the entire jet engine testing process using the pollution prevention paradigm. The process was divided into three parts:

- pre-combustion inputs (fuel and the ambient air),
- the engine itself, and
- the post-combustion exhaust.

Each of these phases was viewed as an opportunity to reduce emissions. Modeling these three phases as decisions to make, and modeling how the attributes listed above would be affected by these decisions resulted in the macroscopic influence diagram contained in Figure 38. In Chapter Three, the four attribute value nodes are modeled using influence

diagrams. Chapter Four describes how uncertainty and preference structure are incorporated into the model.

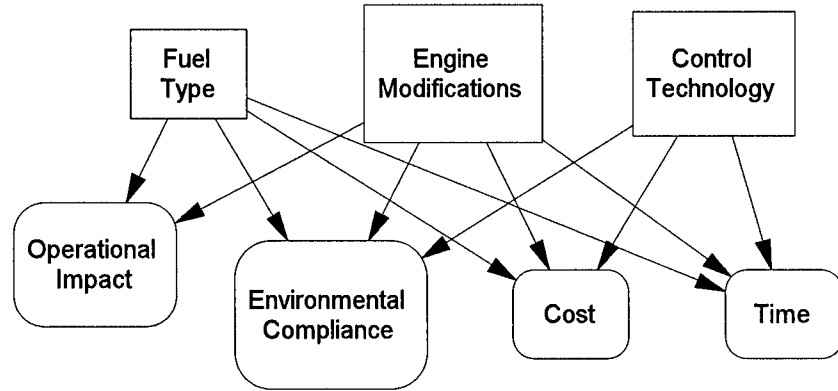


Figure 38 Macroscopic Influence Diagram

The decision support model developed in this research compares the impacts and benefits of the various technologies available now or in the future to reduce emissions during jet engine testing. Rather than providing the decision maker a single utility for each alternative decision strategy, this model allows the decision maker to see the operational impact, environmental benefit, cost, and time to field on a single graph. By displaying all four attributes, the model's output allows helps the decision maker make a more informed decision than would be possible without the model.

Data Analysis and Conclusions. While the data in this thesis is notional, it is based upon several real technology options uncovered during the literature review. Appendix B contains a summary of the data used in this research. Figure 39 shows a strategy generation table with the alternative technologies compared in this research.

Strategy Generation Table


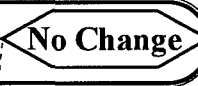

Strategy	<i>Pre-Process</i>	<i>Within Process</i>	<i>Post-Process</i>
	<i>Fuels</i>	<i>Engine</i>	<i>Control Technology</i>
Baseline Strategy →		No Change	
Short Term Strategy □	Additive	Modify Engine	Control Technology 1
Long Term Strategy ⬡			OR Control Technology 2

Figure 39 Strategy Generation Table

An examination of this highly uncertain data shows two interesting facts. First, the cost of developing and fielding a new fighter engine is three orders of magnitude greater than the cost of developing and fielding a jet engine test cell control technology. For this reason, the use of new environmentally friendly fighter engines to reduce emissions during jet engine testing is not a cost-effective option. However, the Integrated High Performance Turbine Engine Technology (IHPTET) demonstration program will, most likely, produce engines that have lower emissions. This fact should be kept in mind because the new engines may eventually lower emissions enough that the control technologies are not generally needed.

These future lower emissions may affect the required life expectancy of the control technologies. Additionally, environmentally fighter engines will reduce pollution whenever they are in operation not just when the engines are being tested. Also, because

some technologies, such as selective catalytic reduction, greatly increase in cost per ton NO_x removed when the parts per million NO_x in the exhaust stream is reduced, the projected reduction in future emissions may affect the choice of control technology today.

This research shows that the best short term approach to jet engine test cell emissions reduction is to use a control technology. However, if new engine designs do result in lower operational emissions, control technologies may not be needed in the future.

Second, fuel does not appear to have much ability to reduce emissions during jet engine testing but could reduce emissions overall. This is because a fuel that reduced emissions by a small amount whenever the engine is in operation would have a greater effect on the ambient air than a great reduction in the test cell. The change in emissions caused by converting to JP-8+100 fuel may provide some insight into the potential of fuel changes to affect emissions. However, JP-8+100 emission testing has not occurred and the emissions factors for the F110 engine using JP-8 fuel were not available.

Future Research.

This research project has uncovered several topics that should be investigated further:

- This research used notional data based on actual technologies under development. The model should be used to analyze actual data for alternatives for each decision in the model. The data needed to do this was not available to the researcher.

- Considering technology risk could improve this model. Currently, the model assumes that all technologies can be developed. This means that if enough time and money are expended developing a technology, the technology will be successfully developed. A risk factor could be incorporated into the model that represents the probability that a technology cannot be developed.

- The current jet engine test cells use a tremendous amount of bypass air to cool the jet engine during testing. Could the jet engine test cell be designed differently so that the bypass air used to cool the engine is not mixed with the engine exhaust so that the volume of air treated by a control technology would be smaller? It is this large volume of air and strict back pressure requirements that make jet engine test cell control technology a challenging design problem.

- The jet engine test cell emits only a small amount of pollution compared to air field operations. This model could be used to compare the potential to reduce pollution in the test cell with the overall reduction possible if a new fuel or engine modification was used. If an emission reducing fuel is used in both the test cell and in air operations, the reductions of overall pollution may be substantial compared with an 80+ percent reduction of emissions from the test cell.

Appendix A: Decision Analysis Overview

Introduction

This appendix provides the reader a short description of decision analysis and decision analysis terms as they are used in this research. First, it explains the purpose of decision analysis. Next, it describes the structure of decision problems. Then, it explains the methods for quantifying key uncertainties. Finally, it discusses the modeling of the decision maker's preference structure.

The Purpose of Decision Analysis

“The purpose of decision analysis is to help a decision maker think systematically about complex problems and to improve the quality of the resulting decisions” (Clemen, 1990:9). To this end,

Decision analysis provides an effective method for organizing a complex problem into a structure that can then be analyzed. In particular, elements of a decision's structure include the possible outcomes of action, the possible outcomes that could result, the likelihood of those outcomes, and the costs and benefits to be derived from the different outcomes (Clemen, 1990:2).

Decision analysis assists the decision maker by clarifying the important issues and reducing a complex problem to its simpler component parts. Ronald A. Howard, a decision analysis pioneer, further describes decision analysis as

a systematic procedure for transforming opaque decision problems into transparent decision problems by a sequence of transparent steps. Opaque means ‘hard to understand, solve or explain; not simple, clear, or lucid.’ Transparent means ‘readily understood, clear, obvious.’ In other words, decision analysis offers the possibility to a decision maker of replacing

confusion by clear insight into a desired course of action (Howard, 1988:680).

As it is used in this research, decision analysis “is not *descriptive*, because most people do not attempt to think systematically about hard choices under uncertainty. It is also not *normative* since it is not an idealized theory designed for the superrational being with an all powerful intellect” (Kenney and Raiffa, 1993: xv). Instead, it is a *prescriptive* approach designed for the normally intelligent person who wants to think hard and systematically about an important real problem (Kenney and Raiffa, 1993: xv).

Some additional discussion of these three purposes may be needed. Descriptive analysis studies the decisions people make and how they decide. Normative analysis attempts to produce logically consistent decision procedures and recommends alternatives based on how people should decide. Prescriptive analysis tries to help people make good decisions and to train people to make better decisions. The lines between these three studies are not sharply defined and there is much overlap (Bell, Raiffa, and Tversky, 1988:2-3).

The prescriptive nature of decision analysis is important. However, the goal of decision analysis is to provide guidance, not solutions. Instead of providing solutions, decision analysis provide structure and guidance which act as an information source that provides insight about the situation, uncertainty, objectives, tradeoffs, and possibly results for a recommended course of action.

The Process

The first step in the decision analysis process is identifying the elements of the problem. These elements can be classified into one of three categories: decisions to make, uncertain events, and the value of the specific outcomes (Clemen, 1990:17).

Decisions to Make. Identifying the immediate *decisions to make* is the critical first step in understanding a difficult decision situation. A decision is an irrevocable allocation of resources. That is, once a decision is made, resources are allocated and unrecoverable. A decision model cannot be developed without knowing exactly what the decision or decisions to make are. Thinking about possible alternatives is important, when identifying the central decisions. Some decisions will have specific alternatives, while others may involve choosing a specific value out of a range of possible values (Clemen, 1992:18). For example, a CEO of soda company can decide to market or not to market a new soft drink. The same CEO can also decide to price the new drink with a wholesale cost between 10 cents and 30 cents per can. Beyond alternatives that dictate a course of action, a decision maker should also consider the alternatives of doing nothing, of waiting for further information, or of hedging bets (Clemen, 1990:18).

One good way to display all the required decisions and the alternatives for each is a *strategy-generation table*. The strategy-generation table allows the analyst and the decision maker to focus on the complete decision problem rather than the individual decisions. By using a strategy-generation table the decision maker can focus on a small number of feasible alternative strategies rather than the large number of alternative

strategies available through mathematical permutations (Howard, 1988:684-685). In addition to displaying alternatives already developed, a strategy-generation table is an important method for creating additional alternatives. In 1988, Howard stated that the strategy-generation table was “the most important idea in creating alternatives” (Howard, 1988:684).

Figure 40 shows an example of a strategy-generation table. In this example, an Air Force commander must develop a plan to ensure air superiority. The decisions to make are: what type of aircraft to use, the number of aircraft to use, and which target to attack. The table lists alternatives for each of these decisions. Additionally, it names a decision strategy and notes the possibility of others. The graphical representation of the decisions and alternatives found in the strategy-generation table helps to make the alternatives clear.

Air Superiority Mission Profile

Strategy Theme	Type of Aircraft	Number of Aircraft	Target to Attack
Dogfight	B-1B	15	Hardened Aircraft Shelter
Disable Aircraft	F-15E	10	Airfield
Destroy on the Ground	F-16	5	Aircraft in the Air

Figure 40 Sample Strategy-Generation Table

Uncertain Events. *Uncertain events* typically complicate decision problems. Many important decisions must be made without knowing exactly what the future holds or

exactly what the ultimate outcome will be. A classic decision made under uncertainty is a stock purchase. An investor wishes to purchase some stock and must decide which stock is best. The investor has several uncertainties to consider. Some stocks will increase in value and some will decrease. Additionally, complex market forces may drive the entire market up or down. The best an investor can do is consider the chances associated with each stock's price and the applicable market forces and then decide accordingly. The point of the example is that the outcome of the uncertain events comes from a range of possible values (Clemen, 1990:19).

Only after the decision maker has made all the required decisions and waited for the uncertain events to be resolved, can he or she see the value of the final outcome.

It may be a matter of profit or loss . . . In some cases the final value may be a 'net value' figure that accounts for both cash outflows and inflows during the time sequence of decisions. This might happen in the case of the manufacturer deciding about a new product; certain loss might be incurred . . . before any revenue is obtained (Clemen, 1990:20-21).

Value of Outcomes. In many decision problems, reducing the final outcome to a single factor like dollars is possible. In general, however, the outcome of a decision problem will be multidimensional. That is, the outcome will have multiple attributes that cannot be reduced to a single measure. "Consider the outcome of a general's decision to storm a hill. The outcome might be good because the army succeeds in taking the hill, but it might be bad at the same time because of the lives lost" (Clemen, 1990:21).

Examples of objectives are minimize total cost, maximize customers served, and maximize profits. It is quite likely that the objectives of a decision problem will conflict. This conflict results in one objective being accomplished only at the expense of another (Keeney and Raiffa, 1993:33). Objectives are broken down into broad overall concerns and detailed sub-objectives. For example, the mayor of a large city may be concerned with the health of the city's citizens. After studying this broad *area of concern*, the mayor determines that reducing air pollution will help improve the health of the city's citizens. Reducing air pollution is now an objective of the mayor. Further study shows that reducing sulfur dioxide emissions and nitrogen oxides emissions will further the objective of reducing air pollution. Reducing each one of these emissions now becomes a sub-objective (Keeney and Raiffa, 1993:32).

Each lower level objective must be measured in terms of an attribute. An attribute is a definable quantity such as pounds, dollars or days. The objective of reducing sulfur dioxide emissions can be measured in terms of the attribute, pounds of sulfur dioxide reduced.

Structuring the Problem

Decision analysis offers two approaches for structuring problems: influence diagrams and decision trees (Clemen, 1990:34).

Influence Diagrams. An influence diagram captures the decision maker's state of information as a simple graphical representation of a decision problem. The elements of

the decision problem -- decisions to make, uncertain events, and the values of outcomes -- appear in the influence diagram as different shapes (Parnell, 1995:3-1). These shapes, shown in Figure 41, are known as decision nodes, chance nodes and value nodes respectively. The nodes are linked by arrows known as arcs.

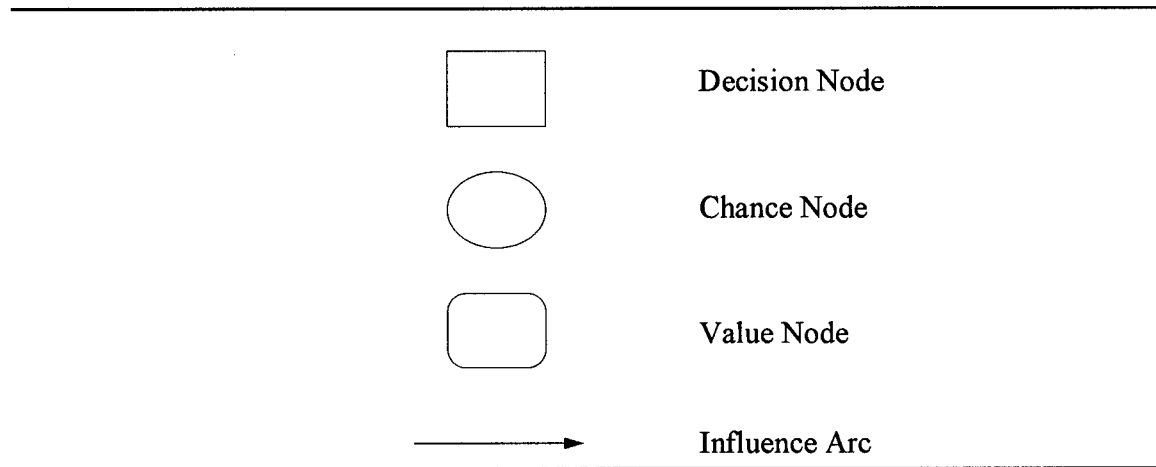


Figure 41 Influence Diagram Elements

The arcs connect the nodes in specific ways that show the relationships between the nodes. There are two types of arcs: relevance arcs and knowledge arcs. A relevance arc points into either a chance or a value node. This type of arc shows that the outcome of the event at the tail of the arc is relevant to the outcome of the event at the head of the arc. Similarly, an information arc points into a decision node. An information arc shows that the outcome of the event node at the tail of the arc is known before the decision at the head of the arc is made. Figure 42 shows this relationship.

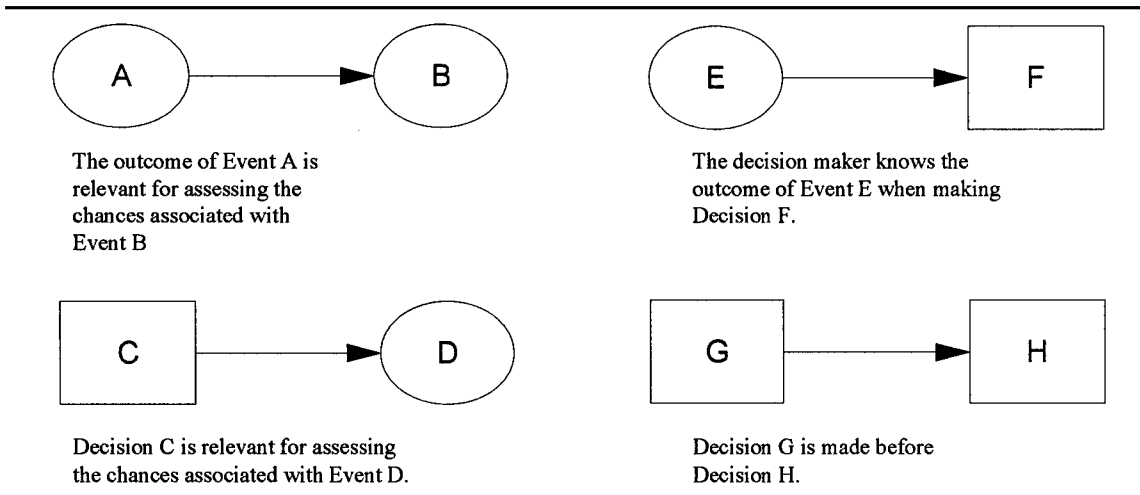


Figure 42 The Meaning of Influence Arcs (Adapted from Clemen, 1992:36)

Figure 43 shows an example of an influence diagram for the most basic of decision problems. This problem has one decision and one uncertain event that together affects the outcome represented by the node **VALUE**. Before the outcome, **VALUE**, is known, both the decision to be made and the uncertain event must be resolved.

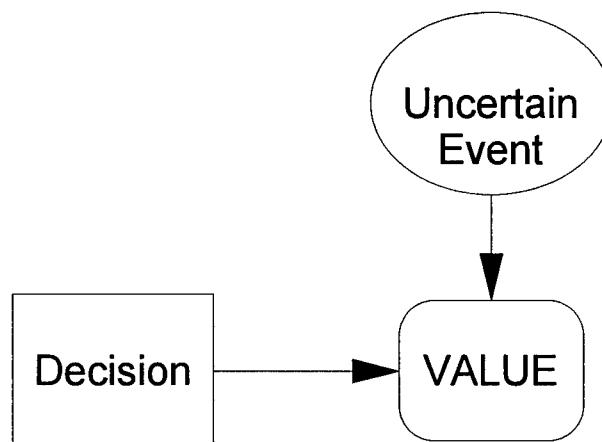


Figure 43 Generic Influence Diagram

Decision Trees. The second approach for structuring decisions is the decision tree. Decision trees are needed because while influence diagrams do an excellent job of showing the structure of a decision problem, they hide many of the problem's details. Similar to

influence diagrams, in influence diagrams squares represent decisions to be made, and circles represent chance events.

The branches emanating from a square correspond to the choices available to the decision maker, and the branches from a circle represent the possible outcomes of a chance event. The third decision element, the value of the outcomes is specified at the end each branch (Clemen, 1990:49).

Several items should be kept in mind when interpreting decision trees:

- The options represented by branches from a decision node must be such that the decision maker can choose only one option.
- Each chance node must have branches that correspond to a set of mutually exclusive and collectively exhaustive outcomes. *Mutually exclusive* means only one of the outcomes can happen. *Collectively exhaustive* means no other possibilities exist and one of the outcomes must occur.
- A decision tree represents all possible paths that the decision maker might follow through time.
- Thinking of the nodes as occurring in a time sequence is sometimes useful. Beginning on the left side of the tree, a decision typically happens first, and then is followed by other decisions or chance events in chronological order (Clemen, 1990:50).

Figure 44 shows the nodes and branches of a generic decision tree.

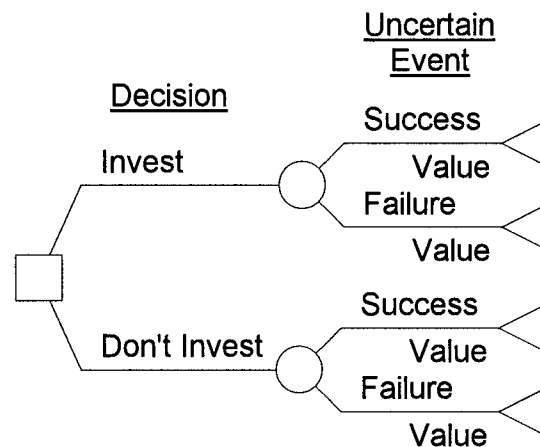


Figure 44 Generic Decision Tree

Because a complex decision problem has many nodes, the decision tree that represents the problem can quickly become excessively large and cluttered. To simplify this, a shorthand diagram for decision trees has been developed. Figure 45 contains a compact version of the tree shown in Figure 44. The fact that the uncertain event is placed after the decision node but is not attached to any of the decision's branches shows that the uncertain event occurs after the decision without regard to the outcome of the decision. This shorthand diagram keeps the important relationships of the decision problem clear and uncluttered.

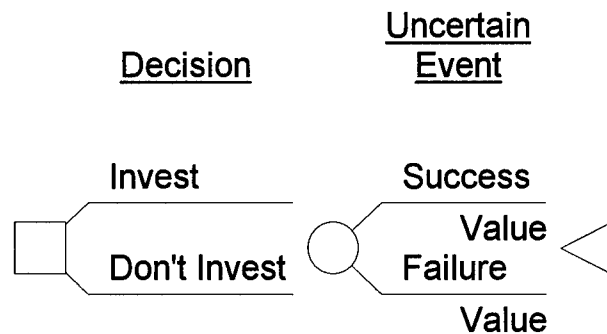


Figure 45 Shorthand Generic Decision Tree

Modeling Probability and Uncertainty.

After capturing the structure of the decision problem using an influence diagram and decision tree, the next step in the process in capturing the key uncertainties in the model.

A central principal of decision analysis is that appropriate probabilities can represent each type of uncertainty. (Clemen, 1990:169)

Many uncertain events are quantitative. . . The set of probabilities associated with all possible outcomes of an uncertain quantity is called its *probability distribution*. . . . Of course, the probabilities in a probability distribution must add to 1 because the events -- numerical outcomes -- are mutually exclusive. Uncertain quantities (sometimes called random

variables) and their probability distributions play a central role in decision analysis. (Clemen, 1992:176)

Not all uncertainties are fully characterized during sensitivity analysis. Sensitivity analysis uses tornado diagrams and rainbow diagrams to identify those variables that can range in values enough to change the recommended decision. A tornado diagram is an “ordered sensitivity analysis” (Howard, 1988:691). The values analyzed using a tornado diagram are ordered from top to bottom by their ability to affect the preferred decision. Figure 46 contains a sample tornado distribution.

The values in the tornado diagram below is ordered in terms of the ability of the values to affect the value of the decision. However, it is those nodes that have a change in color that are key uncertainties. This is because the change in color indicates the ability of the value to change the preferred decision. In the case of this generic diagram, Event 1b and Event 1 should be quantified as a probability distribution in the decision model.

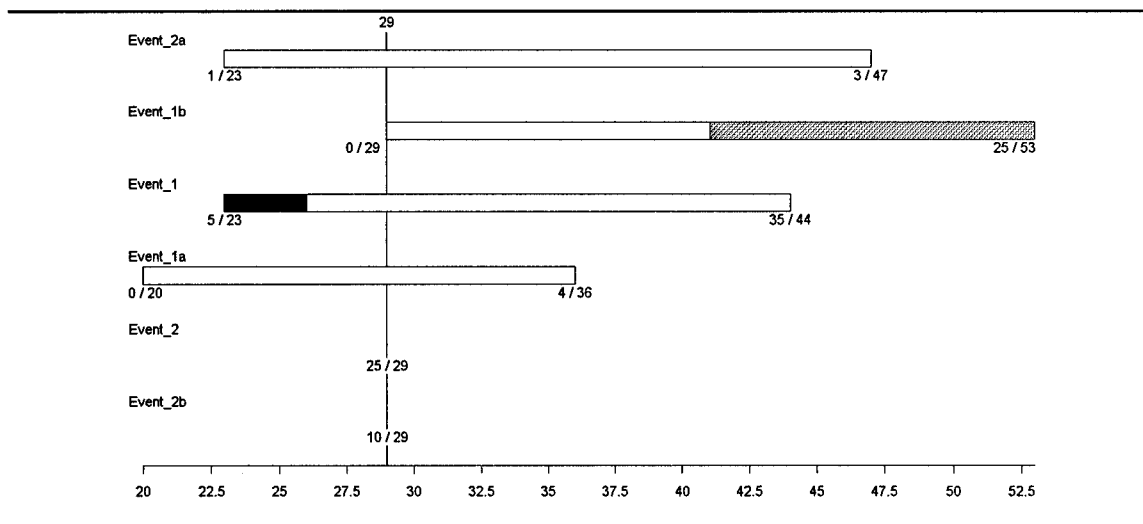


Figure 46 Generic Tornado Diagram

Only the uncertainties, considered key to the analysis, are fully characterized by probability distributions. The other uncertain events are characterized using expected values because the exact distribution is unneeded because these events cannot change the recommended decision.

Incorporating Decision Maker Preference and Utility Into the Model.

The final step in creating a decision model is identifying and modeling the preference structure of the decision maker. Because most complex decision problems involve multiple objectives that conflict, the decision maker is faced with the problem of achieving one objective to the detriment of the others. This phenomenon is known as value tradeoff. (Kenney and Raiffa, 1993: 66) By modeling the preference structure of the decision maker, the analyst can weigh the values of the objectives against one another and come up with the alternative strategy that has the highest overall utility.

Utility is the overall usefulness score given to each alternative using the decision maker's preference structure. Typically, the most useful alternative has a normalized utility of one. The worst alternative has a normalized utility of zero. In this way, the model can rank order the alternative strategies from best to worst based on the decision maker's preferences.

Appendix B: Summary of Data

Option: Fuel Additive	Environmental Benefit Estimated Percent Reduction Per Mode													
	NOx			CO			UHC			SO2			PM	
	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Max
Idle	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	7%
30%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	7%
80%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	7%
100%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	7%
After burner	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	5%	7%	3%	7%

Estimated Costs in Excess of JP-8, Current Engine, No Control Technology	
Research And Development Costs:	\$100K - \$300K (point estimate: \$225K)
Acquisition Costs:	\$10K - 20K (point estimate: \$12K)
Facility Costs:	none
Operation and Maintenance Costs:	\$187K - \$47K per year (point estimate: \$93.5K)

Estimated Time to Develop and Implement	
Research and Development Time:	2 - 4 years (point estimate: 3 years)
Implementation Time:	3 - 5 years (point estimate: 4 years)

Operational Impact of the Alternative	
Engine Performance:	99 out of 100
Other Operational Considerations:	98 - 99 out of 100 (point estimate: 99)
Other Testing Factors:	100 out of 100 Not applicable (Same fuel in testing and in operation)
Back Pressure (Ctrl Tech Only):	0 inches

Figure 47 Notional Fuel Additive Data

Option: Engine Modification (Staged Combustor)

**Environmental Benefit
Estimated Percent Reduction Per Mode**

	NO _x			CO			UHC			SO ₂			PM		
	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Idle	0%	3%	5%	0%	3%	5%	30%	35%	0%			0%		3%	5%
30%	0%	3%	5%	0%	3%	5%	30%	35%	0%			0%		3%	5%
80%	0%	3%	5%	0%	3%	5%	30%	35%	0%			0%		3%	5%
100%	0%	3%	5%	0%	3%	5%	30%	35%	0%			0%		3%	5%
After burner	0%	3%	5%	0%	3%	5%	30%	35%	0%			0%		3%	5%

Estimated Costs in Excess of JP-8, Current Engine, No Control Technology

Research And Development Costs: \$3M - \$5M (point estimate: \$4M)

Acquisition Costs: \$1.62M - \$2.16M (point estimate: \$1.89M) x 50 aircraft = \$81M - \$108M (point estimate: \$94.5M)

Facility Costs: none

Operation and Maintenance Costs: no change

Estimated Time to Develop and Implement

Research and Development Time: 2 - 4 years (point estimate: 3 years)

Implementation Time: 5 - 7 years (point estimate: 6 years)

Operational Impact of the Alternative

Engine Performance: 97 - 99 out of 100 (point estimate: 98)

Other Operational Considerations: 98 - 100 out of 100 (point estimate: 99) Engine would perform for the pilot like current engine.

Other Testing Factors: 100 out of 100 Not applicable (Same engine in testing and in operation)

Back Pressure (Ctrl Tech Only): 0 inches

Figure 48 Notional Engine Modification Data

Option: New Engine Design (Staged Combustor)

**Environmental Benefit
Estimated Percent Reduction Per Mode**

	NO _x			CO			UHC			SO ₂			PM		
	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Idle	0%	5%	10%	0%	5%	10%	0%	35%	45%	0%	0%	0%	0%	5%	10%
30%	0%	5%	10%	0%	5%	10%	35%	40%	45%	0%	0%	0%	0%	5%	10%
80%	0%	5%	10%	0%	5%	10%	35%	40%	45%	0%	0%	0%	0%	5%	10%
100%	0%	5%	10%	0%	5%	10%	35%	40%	45%	0%	0%	0%	0%	5%	10%
After burner	0%	5%	10%	0%	5%	10%	35%	40%	45%	0%	0%	0%	0%	5%	10%

Estimated Costs in Excess of JP-8, Current Engine, No Control Technology

Research And Development Costs: \$3M - \$5M (point estimate: \$4M)

Acquisition Costs: \$5.67M - \$5.94M (point estimate: \$5.83M) x 50 aircraft = \$283.5M - \$297M (point estimate: \$291.6M)

Facility Costs: none

Operation and Maintenance Costs: no change

Estimated Time to Develop and Implement

Research and Development Time: 2 - 4 years (point estimate: 3 years)

Implementation Time: 2 - 4 years (point estimate: 3 years)

Operational Impact of the Alternative

Engine Performance: 100 out of 100 (point estimate: 100)

Other Operational Considerations: 100 out of 100 (point estimate: 99) Engine would perform for the pilot like current engine.

Other Testing Factors: 100 out of 100 Not applicable (Same engine in testing and in operation)

Back Pressure (Ctrl Tech Only): 0 inches

Figure 49 Notional New Engine Design Data

Option: Control Technology 1 (Based on Sorbent Bed w/ Activated Carbon)

**Environmental Benefit
Estimated Percent Reduction Per Mode**

	NO _x			CO			UHC			SO ₂			PM		
	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Idle	20%	25%	30%	25%	30%	35%	50%	55%	60%	50%	55%	60%	50%	55%	60%
30%	20%	25%	30%	25%	30%	35%	50%	55%	60%	50%	55%	60%	50%	55%	60%
80%	20%	25%	30%	25%	30%	35%	50%	55%	60%	50%	55%	60%	50%	55%	60%
100%	20%	25%	30%	25%	30%	35%	50%	55%	60%	50%	55%	60%	50%	55%	60%
After burner	20%	25%	30%	25%	30%	35%	50%	55%	60%	50%	55%	60%	50%	55%	60%

Estimated Costs in Excess of JP-8, Current Engine, No Control Technology

Research And Development Costs: \$100K - \$200K (point estimate: \$150K)

Acquisition Costs: \$100K - \$200K (point estimate: \$150K)

Facility Costs: \$60K - \$80K (point estimate: \$70K)

Operation and Maintenance Costs: \$17.6K - \$70.6K per year (point estimate: \$35.3K) based on \$1 - \$4 /lb NO_x (point estimate: \$2/lb NO_x) * 8.83 tons NO_x

Estimated Time to Develop and Implement

Research and Development Time: 1 - 2 years (point estimate: 1 years)

Implementation Time: 1 - 2 years (point estimate: 2 years)

Operational Impact of the Alternative

Engine Performance: No operational impact outside test cell

Other Operational Considerations: No operational impact outside test cell

Other Testing Factors: 98 - 100 out of 100 (point estimate: 99) Potential effects of using a control technology

Back Pressure (Ctrl Tech Only): 0.50 - 0.75 inches (point estimate: 0.66 inches)

Figure 50 Notional Control Technology 1 Data

Option: Control Technology 2 (Based on Pulse Plasma Concept)

**Environmental Benefit
Estimated Percent Reduction Per Mode**

	NO _x			CO			UHC			SO ₂			PM		
	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Idle	60%	65%	70%	40%	50%	65%	80%	85%	90%	40%	45%	50%	40%	45%	50%
30%	60%	65%	70%	40%	50%	65%	80%	85%	90%	40%	45%	50%	40%	45%	50%
80%	60%	65%	70%	40%	50%	65%	80%	85%	90%	40%	45%	50%	40%	45%	50%
100%	60%	65%	70%	40%	50%	65%	80%	85%	90%	40%	45%	50%	40%	45%	50%
After burner	60%	65%	70%	40%	50%	65%	80%	85%	90%	40%	45%	50%	40%	45%	50%

Estimated Costs in Excess of JP-8, Current Engine, No Control Technology

Research And Development Costs: \$300K - \$500K (point estimate: \$400K)

Acquisition Costs: \$100K - \$300K (point estimate: \$200K)

Facility Costs: \$30K- \$50K (point estimate: \$40K)

Operation and Maintenance Costs: \$4.4K - \$17.7K per year (point estimate: \$8.8K) based on \$0.25 - \$1 /lb NO_x (pt estimate: \$0.50/lb NO_x) * 8.83 tons NO_x

Estimated Time to Develop and Implement

Research and Development Time: 2 - 3 years (point estimate: 3 years)

Implementation Time: 1 - 2 years (point estimate: 2 years)

Operational Impact of the Alternative

Engine Performance: No operational impact outside test cell

Other Operational Considerations: No operational impact outside test cell

Other Testing Factors: 97 - 99 out of 100 (point estimate: 98) Potential effects of using a control technology

Back Pressure (Ctrl Tech Only): 0.33 - 0.66 inches (point estimate: 0.50 inches)

Figure 51 Notional Control Technology 2 Data

Appendix C: DPL Language Program for Deterministic Analysis

```

value EP_Weight=0.33;
value OOC_Weight=0.33;
value TP_Weight=1-EP_Weight-OOC_Weight;
value Interest_Rate=0.079;
value Time_Horizon=30;
value W1=2/7;
value W2=2/7;
value W3=1/7;
value W4=1/7;
value W5=1/7;
decision Fuel_Type.{JP_8,Additive};
decision Engine_Modifications.{No_Change,Modify_Engine,New_Engine};
decision Control_Technology.{No_Change,Sorbent_Bed,Pulsed_Plasma};
value EP_Fuel_Impact|Fuel_Type=
    100, // Fuel_Type.JP_8
    99; // Fuel_Type.Additive
value EP_EM_Impact|Engine_Modifications=
    100, // Engine_Modifications.No_Change
    98, // Engine_Modifications.Modify_Engine
    100; // Engine_Modifications.New_Engine
value OOC_Fuel_Impact|Fuel_Type=
    100, // Fuel_Type.JP_8
    99; // Fuel_Type.Additive
value OOC_EM_Impact|Engine_Modifications=
    100, // Engine_Modifications.No_Change
    98, // Engine_Modifications.Modify_Engine
    100; // Engine_Modifications.New_Engine
value Back_Pressure|Control_Technology=
    0, // Control_Technology.No_Change
    0.66, // Control_Technology.Sorbent_Bed
    0.5; // Control_Technology.Pulsed_Plasma
value OTF_Fuel_Impact|Fuel_Type=
    100, // Fuel_Type.JP_8
    100; // Fuel_Type.Additive
value OTF_CT_Impact|Control_Technology=
    100, // Control_Technology.No_Change
    99, // Control_Technology.Sorbent_Bed
    98; // Control_Technology.Pulsed_Plasma
value NOx_Fuel_Impact|Fuel_Type=
    0.00, // Fuel_Type.JP_8
    0.05; // Fuel_Type.Additive
value NOx_EM_Impact|Engine_Modifications=
    0.00, // Engine_Modifications.No_Change
    0.35, // Engine_Modifications.Modify_Engine
    0.40; // Engine_Modifications.New_Engine
value NOx_CT_Impact|Control_Technology=
    0.00, // Control_Technology.No_Change
    0.55, // Control_Technology.Sorbent_Bed
    0.85; // Control_Technology.Pulsed_Plasma
value CO_Fuel_Impact|Fuel_Type=
    0.00, // Fuel_Type.JP_8

```

```

0.05;
value CO_EM_Impact|Engine_Modifications=
0.00,
0.03,
0.05;
value CO_CT_Impact|Control_Technology=
0.00,
0.30,
0.50;
value SO2_Fuel_Impact|Fuel_Type=
0.00,
0.00;
value SO2_EM_Impact|Engine_Modifications=
0.00,
0.00,
0.00;
value SO2_CT_Impact|Control_Technology=
0.00,
0.55,
0.45;
value PM_Fuel_Impact|Fuel_Type=
0.00,
0.05;
value PM_EM_Impact|Engine_Modifications=
0.00,
0.03,
0.05;
value PM_CT_Impact|Control_Technology=
0.00,
0.55,
0.45;
value R_D_Fuel_Cost|Fuel_Type=
0,
225000;
value R_D_EM_Cost|Engine_Modifications=
0,
4000000,
4000000;
value R_D_CT_Cost|Control_Technology=
0,
150000,
400000;
value Acq_Fuel_Cost|Fuel_Type=
0,
12000;
value Acq_EM_Cost|Engine_Modifications=
0,
94500000,
291600000;
value Acq_CT_Cost|Control_Technology=
0,
150000,
200000;
value Fac_Fuel_Cost|Fuel_Type=
// Fuel_Type.Additive
// Engine_Modifications.No_Change
// Engine_Modifications.Modify_Engine
// Engine_Modifications.New_Engine
// Control_Technology.No_Change
// Control_Technology.Sorbent_Bed
// Control_Technology.Pulsed_Plasma
// Fuel_Type.JP_8
// Fuel_Type.Additive
// Engine_Modifications.No_Change
// Engine_Modifications.Modify_Engine
// Engine_Modifications.New_Engine
// Control_Technology.No_Change
// Control_Technology.Sorbent_Bed
// Control_Technology.Pulsed_Plasma
// Fuel_Type.JP_8
// Fuel_Type.Additive
// Engine_Modifications.No_Change
// Engine_Modifications.Modify_Engine
// Engine_Modifications.New_Engine
// Control_Technology.No_Change
// Control_Technology.Sorbent_Bed
// Control_Technology.Pulsed_Plasma
// Fuel_Type.JP_8
// Fuel_Type.Additive
// Engine_Modifications.No_Change
// Engine_Modifications.Modify_Engine
// Engine_Modifications.New_Engine
// Control_Technology.No_Change
// Control_Technology.Sorbent_Bed
// Control_Technology.Pulsed_Plasma

```

```

0, // Fuel_Type.JP_8
0; // Fuel_Type.Additive
value Fac_CT_Cost|Control_Technology=
0, // Control_Technology.No_Change
70000, // Control_Technology.Sorbent_Bed
40000; // Control_Technology.Pulsed_Plasma
value O_M_Fuel_Cost|Fuel_Type=
0, // Fuel_Type.JP_8
935000; // Fuel_Type.Additive
value O_M_EM_Cost|Engine_Modifications=
0, // Engine_Modifications.No_Change
0, // Engine_Modifications.Modify_Engine
0; // Engine_Modifications.New_Engine
value O_M_CT_Cost__Baseline_|Control_Technology=
0, // Control_Technology.No_Change
35300, // Control_Technology.Sorbent_Bed
8832; // Control_Technology.Pulsed_Plasma
value Imp_Fuel_Time|Fuel_Type=
0, // Fuel_Type.JP_8
4; // Fuel_Type.Additive
value Imp_EM_Time|Engine_Modifications=
0, // Engine_Modifications.No_Change
6, // Engine_Modifications.Modify_Engine
3; // Engine_Modifications.New_Engine
value Imp_CT_Time|Control_Technology=
0, // Control_Technology.No_Change
2, // Control_Technology.Sorbent_Bed
2; // Control_Technology.Pulsed_Plasma
value R_D_Fuel_Time|Fuel_Type=
0, // Fuel_Type.JP_8
3; // Fuel_Type.Additive
value R_D_EM_Time|Engine_Modifications=
0, // Engine_Modifications.No_Change
3, // Engine_Modifications.Modify_Engine
3; // Engine_Modifications.New_Engine
value R_D_CT_Time|Control_Technology=
0, // Control_Technology.No_Change
1, // Control_Technology.Sorbent_Bed
3; // Control_Technology.Pulsed_Plasma
value Backpressure_Threshold=@if(Back_Pressure>1,0,1);
value UHC_Fuel_Impact|Fuel_Type=
0.00, // Fuel_Type.JP_8
0.05; // Fuel_Type.Additive
value UHC_EM_Impact|Engine_Modifications=
0.00, // Engine_Modifications.No_Change
0.03, // Engine_Modifications.Modify_Engine
0.05; // Engine_Modifications.New_Engine
value UHC_CT_Impact|Control_Technology=
0.00, // Control_Technology.No_Change
0.25, // Control_Technology.Sorbent_Bed
0.65; // Control_Technology.Pulsed_Plasma
value UHC=UHC_Fuel_Impact+UHC_EM_Impact*(1-UHC_Fuel_Impact)+
UHC_CT_Impact*(1-(UHC_Fuel_Impact+UHC_EM_Impact*(1-UHC_Fuel_Impact)));

```

```

value Annual_R_D_Fuel_Cost=@if(R_D_Fuel_Time==
0,R_D_Fuel_Cost,R_D_Fuel_Cost/R_D_Fuel_Time);
value Annual_R_D_EM_Cost=@if(R_D_EM_Time==0,R_D_EM_Cost,R_D_EM_Cost/R_D_EM_Time);
value Annual_R_D_CT_Cost=@if(R_D_CT_Time==0,R_D_CT_Cost,R_D_CT_Cost/R_D_CT_Time);
value Annual_Acq_Fuel_Cost=@if(Imp_Fuel_Time==0,Acq_Fuel_Cost,Acq_Fuel_Cost/Imp_Fuel_Time);
value Annual_Acq_EM_Cost=@if(Imp_EM_Time==0,Acq_EM_Cost,Acq_EM_Cost/Imp_EM_Time);
value Annual_Acq_CT_Cost=@if(Imp_CT_Time==0,Acq_CT_Cost,Acq_CT_Cost/Imp_CT_Time);
value Annual_Fac_Fuel_Cost=@if(Imp_Fuel_Time==0,Fac_Fuel_Cost,Fac_Fuel_Cost/Imp_Fuel_Time);
value Annual_Fac_CT_Cost=@if(Imp_CT_Time==0,Fac_CT_Cost,Fac_CT_Cost/Imp_CT_Time);
value Annual_O_M_CT_Cost=O_M_CT_Cost_Baseline*(1-NOx_Fuel_Impact)*(1-NOx_EM_Impact);
value Annual_O_M_Fuel_Cost=O_M_Fuel_Cost;
value Annual_O_M_EM_Cost=O_M_EM_Cost;
value Time=@max(R_D_Fuel_Time+Imp_Fuel_Time,R_D_EM_Time+Imp_EM_Time,R_D_CT_Time+
Imp_CT_Time);
value Engine_Performance=(EP_Fuel_Impact)*(EP_EM_Impact)/100;
value Other_Operational_Considerations=(OOC_Fuel_Impact)*(OOC_EM_Impact)/100;
value Back_Pressure_Score=@if(Back_Pressure>1,0,(-0.05*Back_Pressure+1)*100);
value Other_Testing_Factors=(OTF_Fuel_Impact)*(OTF_CT_Impact)/100;
value NOx=NOx_Fuel_Impact+NOx_EM_Impact*(1-NOx_Fuel_Impact)+NOx_CT_Impact*
(1-(NOx_Fuel_Impact+NOx_EM_Impact*(1-NOx_Fuel_Impact)));
value CO=CO_Fuel_Impact+CO_EM_Impact*(1-CO_Fuel_Impact)+CO_CT_Impact*
(1-(CO_Fuel_Impact+CO_EM_Impact*(1-CO_Fuel_Impact)));
value SO2=SO2_Fuel_Impact+SO2_EM_Impact*(1-SO2_Fuel_Impact)+SO2_CT_Impact*
(1-(SO2_Fuel_Impact+SO2_EM_Impact*(1-SO2_Fuel_Impact)));
value PM=PM_Fuel_Impact+PM_EM_Impact*(1-PM_Fuel_Impact)+PM_CT_Impact*
(1-(PM_Fuel_Impact+PM_EM_Impact*(1-PM_Fuel_Impact)));
value R_D_Cost=@pv(Annual_R_D_Fuel_Cost,Interest_Rate,R_D_Fuel_Time)+
@pv(Annual_R_D_EM_Cost,Interest_Rate,R_D_EM_Time)+@pv(Annual_R_D_CT_Cost,
Interest_Rate,R_D_CT_Time);
value Acquisition_Cost=(@pv(Annual_Acq_Fuel_Cost,Interest_Rate,Imp_Fuel_Time)*
(1+Interest_Rate)^(-R_D_Fuel_Time))+(@pv(Annual_Acq_EM_Cost,Interest_Rate,
Imp_EM_Time)*(1+Interest_Rate)^(-R_D_EM_Time))+(@pv(Annual_Acq_CT_Cost,
Interest_Rate,Imp_CT_Time)*(1+Interest_Rate)^(-R_D_CT_Time));
value Facility_Cost=(@pv(Fac_Fuel_Cost,Interest_Rate,Imp_Fuel_Time)*(1+Interest_Rate)^
(-R_D_Fuel_Time))+(@pv(Fac_CT_Cost,Interest_Rate,Imp_CT_Time)*(1+Interest_Rate)^
(-R_D_CT_Time));
value O_M_Cost=(@pv(Annual_O_M_Fuel_Cost,Interest_Rate,(Time_Horizon-R_D_Fuel_Time-
Imp_Fuel_Time))*(1+Interest_Rate)^(-R_D_Fuel_Time-Imp_Fuel_Time))+
(@pv(Annual_O_M_EM_Cost,Interest_Rate,(Time_Horizon-R_D_EM_Time-Imp_EM_Time))*
(1+Interest_Rate)^(-R_D_EM_Time-Imp_EM_Time))+(@pv(Annual_O_M_CT_Cost,
Interest_Rate,(Time_Horizon-R_D_CT_Time-Imp_CT_Time))*(1+Interest_Rate)^(-R_D_CT_Time
-Imp_CT_Time));
value NOx_Threshold=@if(NOx<0.10,0,1);
value CO_Threshold=@if(CO<0.10,0,1);
value Cost=R_D_Cost+Acquisition_Cost+Facility_Cost+O_M_Cost;
value Environmental_Compliance_Score=(W1)*(NOx)+(W2)*(CO)+(W3)*(UHC)+(W4)*(SO2)+
(W5)*(PM);
value Test_Performance=(Other_Testing_Factors)*(Back_Pressure_Score)/100;
value Utility=(NOx_Threshold*CO_Threshold)*(Environmental_Compliance_Score);
value Operational_Impact_Score=Backpressure_Threshold*(EP_Weight*Engine_Performance+
OOC_Weight*Other_Operational_Considerations+TP_Weight*Test_Performance);

sequence( attributes = 4,
objective = $1 );

```

decide to Fuel_Type then
decide to Engine_Modifications then
decide to Control_Technology and get Utility, Operational_Impact_Score, Cost, Time

Appendix D: DPL Language Program for Controlled Node Analysis

```

value EP_Weight=0.33;
value OOC_Weight=0.33;
value TP_Weight=1-EP_Weight-OOC_Weight;
value Interest_Rate=0.079;
value Time_Horizon=30;
value W1=2/7;
value W2=2/7;
value W3=1/7;
value W4=1/7;
value W5=1/7;
controlled Fuel_Type.{JP_8,Additive};
controlled Engine_Modifications.{No_Change,Modify_Engine,New_Engine};
controlled Control_Technology.{No_Change,Sorbent_Bed,Pulsed_Plasma};
value EP_Fuel_Impact|Fuel_Type=
    100, // Fuel_Type.JP_8
    99; // Fuel_Type.Additive
value EP_EM_Impact|Engine_Modifications=
    100, // Engine_Modifications.No_Change
    98, // Engine_Modifications.Modify_Engine
    100; // Engine_Modifications.New_Engine
value OOC_Fuel_Impact|Fuel_Type=
    100, // Fuel_Type.JP_8
    99; // Fuel_Type.Additive
value OOC_EM_Impact|Engine_Modifications=
    100, // Engine_Modifications.No_Change
    98, // Engine_Modifications.Modify_Engine
    100; // Engine_Modifications.New_Engine
value Back_Pressure|Control_Technology=
    0, // Control_Technology.No_Change
    0.66, // Control_Technology.Sorbent_Bed
    0.5; // Control_Technology.Pulsed_Plasma
value OTF_Fuel_Impact|Fuel_Type=
    100, // Fuel_Type.JP_8
    100; // Fuel_Type.Additive
value OTF_CT_Impact|Control_Technology=
    100, // Control_Technology.No_Change
    99, // Control_Technology.Sorbent_Bed
    98; // Control_Technology.Pulsed_Plasma
value NOx_Fuel_Impact|Fuel_Type=
    0.00, // Fuel_Type.JP_8
    0.05; // Fuel_Type.Additive
value NOx_EM_Impact|Engine_Modifications=
    0.00, // Engine_Modifications.No_Change
    0.35, // Engine_Modifications.Modify_Engine
    0.40; // Engine_Modifications.New_Engine
value NOx_CT_Impact|Control_Technology=
    0.00, // Control_Technology.No_Change
    0.55, // Control_Technology.Sorbent_Bed
    0.85; // Control_Technology.Pulsed_Plasma
value CO_Fuel_Impact|Fuel_Type=
    0.00, // Fuel_Type.JP_8
    0.05; // Fuel_Type.Additive

```

```

value CO_EM_Impact|Engine_Modifications=
    0.00, // Engine_Modifications.No_Change
    0.03, // Engine_Modifications.Modify_Engine
    0.05; // Engine_Modifications.New_Engine
value CO_CT_Impact|Control_Technology=
    0.00, // Control_Technology.No_Change
    0.30, // Control_Technology.Sorbent_Bed
    0.50; // Control_Technology.Pulsed_Plasma
value SO2_Fuel_Impact|Fuel_Type=
    0.00, // Fuel_Type.JP_8
    0.00; // Fuel_Type.Additive
value SO2_EM_Impact|Engine_Modifications=
    0.00, // Engine_Modifications.No_Change
    0.00, // Engine_Modifications.Modify_Engine
    0.00; // Engine_Modifications.New_Engine
value SO2_CT_Impact|Control_Technology=
    0.00, // Control_Technology.No_Change
    0.55, // Control_Technology.Sorbent_Bed
    0.45; // Control_Technology.Pulsed_Plasma
value PM_Fuel_Impact|Fuel_Type=
    0.00, // Fuel_Type.JP_8
    0.05; // Fuel_Type.Additive
value PM_EM_Impact|Engine_Modifications=
    0.00, // Engine_Modifications.No_Change
    0.03, // Engine_Modifications.Modify_Engine
    0.05; // Engine_Modifications.New_Engine
value PM_CT_Impact|Control_Technology=
    0.00, // Control_Technology.No_Change
    0.55, // Control_Technology.Sorbent_Bed
    0.45; // Control_Technology.Pulsed_Plasma
value R_D_Fuel_Cost|Fuel_Type=
    0, // Fuel_Type.JP_8
    225000; // Fuel_Type.Additive
value R_D_EM_Cost|Engine_Modifications=
    0, // Engine_Modifications.No_Change
    4000000, // Engine_Modifications.Modify_Engine
    4000000; // Engine_Modifications.New_Engine
value R_D_CT_Cost|Control_Technology=
    0, // Control_Technology.No_Change
    150000, // Control_Technology.Sorbent_Bed
    400000; // Control_Technology.Pulsed_Plasma
value Acq_Fuel_Cost|Fuel_Type=
    0, // Fuel_Type.JP_8
    12000; // Fuel_Type.Additive
value Acq_EM_Cost|Engine_Modifications=
    0, // Engine_Modifications.No_Change
    94500000, // Engine_Modifications.Modify_Engine
    291600000; // Engine_Modifications.New_Engine
value Acq_CT_Cost|Control_Technology=
    0, // Control_Technology.No_Change
    150000, // Control_Technology.Sorbent_Bed
    200000; // Control_Technology.Pulsed_Plasma
value Fac_Fuel_Cost|Fuel_Type=
    0, // Fuel_Type.JP_8

```

```

0; // Fuel_Type.Additive
value Fac_CT_Cost|Control_Technology=
0, // Control_Technology.No_Change
70000, // Control_Technology.Sorbent_Bed
40000; // Control_Technology.Pulsed_Plasma
value O_M_Fuel_Cost|Fuel_Type=
0, // Fuel_Type.JP_8
935000; // Fuel_Type.Additive
value O_M_EM_Cost|Engine_Modifications=
0, // Engine_Modifications.No_Change
0, // Engine_Modifications.Modify_Engine
0; // Engine_Modifications.New_Engine
value O_M_CT_Cost__Baseline_|Control_Technology=
0, // Control_Technology.No_Change
35300, // Control_Technology.Sorbent_Bed
8832; // Control_Technology.Pulsed_Plasma
value Imp_Fuel_Time|Fuel_Type=
0, // Fuel_Type.JP_8
4; // Fuel_Type.Additive
value Imp_EM_Time|Engine_Modifications=
0, // Engine_Modifications.No_Change
6, // Engine_Modifications.Modify_Engine
3; // Engine_Modifications.New_Engine
value Imp_CT_Time|Control_Technology=
0, // Control_Technology.No_Change
2, // Control_Technology.Sorbent_Bed
2; // Control_Technology.Pulsed_Plasma
value R_D_Fuel_Time|Fuel_Type=
0, // Fuel_Type.JP_8
3; // Fuel_Type.Additive
value R_D_EM_Time|Engine_Modifications=
0, // Engine_Modifications.No_Change
3, // Engine_Modifications.Modify_Engine
3; // Engine_Modifications.New_Engine
value R_D_CT_Time|Control_Technology=
0, // Control_Technology.No_Change
1, // Control_Technology.Sorbent_Bed
3; // Control_Technology.Pulsed_Plasma
value Backpressure_Threshold=@if(Back_Pressure>1,0,1);
value UHC_Fuel_Impact|Fuel_Type=
0.00, // Fuel_Type.JP_8
0.05; // Fuel_Type.Additive
value UHC_EM_Impact|Engine_Modifications=
0.00, // Engine_Modifications.No_Change
0.03, // Engine_Modifications.Modify_Engine
0.05; // Engine_Modifications.New_Engine
value UHC_CT_Impact|Control_Technology=
0.00, // Control_Technology.No_Change
0.25, // Control_Technology.Sorbent_Bed
0.65; // Control_Technology.Pulsed_Plasma
value UHC=UHC_Fuel_Impact+UHC_EM_Impact*(1-UHC_Fuel_Impact)+UHC_CT_Impact*
(1-(UHC_Fuel_Impact+UHC_EM_Impact*(1-UHC_Fuel_Impact)));
value Annual_R_D_Fuel_Cost=@if(R_D_Fuel_Time==
0,R_D_Fuel_Cost,R_D_Fuel_Cost/R_D_Fuel_Time);

```



```

value Annual_R_D_EM_Cost=@if(R_D_EM_Time==0,R_D_EM_Cost,R_D_EM_Cost/R_D_EM_Time);
value Annual_R_D_CT_Cost=@if(R_D_CT_Time==0,R_D_CT_Cost,R_D_CT_Cost/R_D_CT_Time);
value Annual_Acq_Fuel_Cost=@if(Imp_Fuel_Time==0,Acq_Fuel_Cost,Acq_Fuel_Cost/Imp_Fuel_Time);
value Annual_Acq_EM_Cost=@if(Imp_EM_Time==0,Acq_EM_Cost,Acq_EM_Cost/Imp_EM_Time);
value Annual_Acq_CT_Cost=@if(Imp_CT_Time==0,Acq_CT_Cost,Acq_CT_Cost/Imp_CT_Time);
value Annual_Fac_Fuel_Cost=@if(Imp_Fuel_Time==0,Fac_Fuel_Cost,Fac_Fuel_Cost/Imp_Fuel_Time);
value Annual_Fac_CT_Cost=@if(Imp_CT_Time==0,Fac_CT_Cost,Fac_CT_Cost/Imp_CT_Time);
value Annual_O_M_CT_Cost=O_M_CT_Cost_Baseline_*(1-NOx_Fuel_Impact)*(1-NOx_EM_Impact);
value Annual_O_M_Fuel_Cost=O_M_Fuel_Cost;
value Annual_O_M_EM_Cost=O_M_EM_Cost;
value Time=@max(R_D_Fuel_Time+Imp_Fuel_Time,R_D_EM_Time+Imp_EM_Time,R_D_CT_Time+
    Imp_CT_Time);
value Engine_Performance=(EP_Fuel_Impact)*(EP_EM_Impact)/100;
value Other_Operational_Considerations=(OOC_Fuel_Impact)*(OOC_EM_Impact)/100;
value Back_Pressure_Score=@if(Back_Pressure>1,0,(-0.05*Back_Pressure+1)*100);
value Other_Testing_Factors=(OTF_Fuel_Impact)*(OTF_CT_Impact)/100;
value NOx=NOx_Fuel_Impact+NOx_EM_Impact*(1-NOx_Fuel_Impact)+NOx_CT_Impact*
    (1-(NOx_Fuel_Impact+NOx_EM_Impact*(1-NOx_Fuel_Impact)));
value CO=CO_Fuel_Impact+CO_EM_Impact*(1-CO_Fuel_Impact)+CO_CT_Impact*(1-(CO_Fuel_Impact+
    CO_EM_Impact*(1-CO_Fuel_Impact)));
value SO2=SO2_Fuel_Impact+SO2_EM_Impact*(1-SO2_Fuel_Impact)+SO2_CT_Impact*
    (1-(SO2_Fuel_Impact+SO2_EM_Impact*(1-SO2_Fuel_Impact)));
value PM=PM_Fuel_Impact+PM_EM_Impact*(1-PM_Fuel_Impact)+PM_CT_Impact*
    (1-(PM_Fuel_Impact+PM_EM_Impact*(1-PM_Fuel_Impact)));
value R_D_Cost=@pv(Annual_R_D_Fuel_Cost,Interest_Rate,R_D_Fuel_Time)+
    @pv(Annual_R_D_EM_Cost,Interest_Rate,R_D_EM_Time)+@pv(Annual_R_D_CT_Cost,
    Interest_Rate,R_D_CT_Time);
value Acquisition_Cost=(@pv(Annual_Acq_Fuel_Cost,Interest_Rate,Imp_Fuel_Time)*(1+Interest_Rate)^
    (-R_D_Fuel_Time))+(@pv(Annual_Acq_EM_Cost,Interest_Rate,Imp_EM_Time)*
    (1+Interest_Rate)^(-R_D_EM_Time))+(@pv(Annual_Acq_CT_Cost,Interest_Rate,Imp_CT_Time)*
    (1+Interest_Rate)^(-R_D_CT_Time));
value Facility_Cost=(@pv(Fac_Fuel_Cost,Interest_Rate,Imp_Fuel_Time)*(1+Interest_Rate)^
    (-R_D_Fuel_Time))+(@pv(Fac_CT_Cost,Interest_Rate,Imp_CT_Time)*(1+Interest_Rate)^
    (-R_D_CT_Time));
value O_M_Cost=(@pv(Annual_O_M_Fuel_Cost,Interest_Rate,(Time_Horizon-R_D_Fuel_Time-
    Imp_Fuel_Time))*(1+Interest_Rate)^(-R_D_Fuel_Time-Imp_Fuel_Time))+
    (@pv(Annual_O_M_EM_Cost,Interest_Rate,(Time_Horizon-R_D_EM_Time-Imp_EM_Time))*
    (1+Interest_Rate)^(-R_D_EM_Time-Imp_EM_Time))+(@pv(Annual_O_M_CT_Cost,
    Interest_Rate,(Time_Horizon-R_D_CT_Time-Imp_CT_Time))*(1+Interest_Rate)^
    (-R_D_CT_Time-Imp_CT_Time));
value NOx_Threshold=@if(NOx<0.10,0,1);
value CO_Threshold=@if(CO<0.10,0,1);
value Cost=R_D_Cost+Acquisition_Cost+Facility_Cost+O_M_Cost;
value Environmental_Compliance_Score=(W1)*(NOx)+(W2)*(CO)+(W3)*(UHC)+(W4)*(SO2)+
    (W5)*(PM);
value Test_Performance=(Other_Testing_Factors)*(Back_Pressure_Score)/100;
value Utility=(NOx_Threshold*CO_Threshold)*(Environmental_Compliance_Score);
value Operational_Impact_Score=Backpressure_Threshold*(EP_Weight*Engine_Performance+
    OOC_Weight*Other_Operational_Considerations+TP_Weight*Test_Performance);

```

sequence:

```

set Fuel_Type.JP_8 then
set Engine_Modifications.No_Change then

```

set Control_Technology.No_Change then
get Operational_Impact_Score then
get Time then
get Cost then
get Utility

Appendix E: DPL Language Program for Controlled Node Chance Analysis

```

value EP_Weight=0.33;
value OOC_Weight=0.33;
value TP_Weight=1-EP_Weight-OOC_Weight;
value Interest_Rate=0.079;
value Time_Horizon=30;
value W1=2/7;
value W2=2/7;
value W3=1/7;
value W4=1/7;
value W5=1/7;
controlled Fuel_Type.{JP_8,Additive};
controlled Engine_Modifications.{No_Change,Modify_Engine,New_Engine};
decision Control_Technology.{No_Change,Sorbent_Bed,Pulsed_Plasma};
chance CO_CT_Impact.{High,Medium,Low}|Control_Technology=
    {1.00,0.00,0.00}, // Control_Technology.No_Change
    triangular(0.25,0.35,0.30), // Control_Technology.Sorbent_Bed
    triangular(0.40,0.65,0.50), // Control_Technology.Pulsed_Plasma
=
    // Control_Technology.No_Change
    0.00, // CO_CT_Impact.High
    0.00, // CO_CT_Impact.Medium
    0.00, // CO_CT_Impact.Low
    // Control_Technology.Sorbent_Bed
    *, // CO_CT_Impact.High
    *, // CO_CT_Impact.Medium
    *, // CO_CT_Impact.Low
    // Control_Technology.Pulsed_Plasma
    *, // CO_CT_Impact.High
    *, // CO_CT_Impact.Medium
    *, // CO_CT_Impact.Low
chance R_D_EM_Cost.{High,Medium,Low}|Engine_Modifications=
    {1.00,0,0}, // Engine_Modifications.No_Change
    triangular(3000000,5000000,4000000), // Engine_Modifications.Modify_Engine
    triangular(3000000,5000000,4000000), // Engine_Modifications.New_Engine
=
    // Engine_Modifications.No_Change
    0, // R_D_EM_Cost.High
    0, // R_D_EM_Cost.Medium
    0, // R_D_EM_Cost.Low
    // Engine_Modifications.Modify_Engine
    *, // R_D_EM_Cost.High
    *, // R_D_EM_Cost.Medium
    *, // R_D_EM_Cost.Low
    // Engine_Modifications.New_Engine
    *, // R_D_EM_Cost.High
    *, // R_D_EM_Cost.Medium
    *, // R_D_EM_Cost.Low
chance R_D_CT_Cost.{High,Medium,Low}|Control_Technology=
    {1.00,0,0}, // Control_Technology.No_Change
    triangular(100000,200000,150000), // Control_Technology.Sorbent_Bed
    triangular(300000,500000,400000), // Control_Technology.Pulsed_Plasma
=

```

```

// Control_Technology.No_Change
0, // R_D_CT_Cost.High
0, // R_D_CT_Cost.Medium
0, // R_D_CT_Cost.Low
// Control_Technology.Sorbent_Bed
*, // R_D_CT_Cost.High
*, // R_D_CT_Cost.Medium
*, // R_D_CT_Cost.Low
// Control_Technology.Pulsed_Plasma
*, // R_D_CT_Cost.High
*, // R_D_CT_Cost.Medium
*, // R_D_CT_Cost.Low
chance Acq_EM_Cost.{High,Medium,Low}|Engine_Modifications=
{1.00,0,0}, // Engine_Modifications.No_Change
triangular(81000000,108000000,94500000), // Engine_Modifications.Modify_Engine
triangular(283500000,297000000,291600000), // Engine_Modifications.New_Engine
=
// Engine_Modifications.No_Change
0, // Acq_EM_Cost.High
0, // Acq_EM_Cost.Medium
0, // Acq_EM_Cost.Low
// Engine_Modifications.Modify_Engine
*, // Acq_EM_Cost.High
*, // Acq_EM_Cost.Medium
*, // Acq_EM_Cost.Low
// Engine_Modifications.New_Engine
*, // Acq_EM_Cost.High
*, // Acq_EM_Cost.Medium
*, // Acq_EM_Cost.Low
chance Fac_CT_Cost.{High,Medium,Low}|Control_Technology=
{1.00,0,0}, // Control_Technology.No_Change
triangular(60000,80000,70000), // Control_Technology.Sorbent_Bed
triangular(30000,50000,40000), // Control_Technology.Pulsed_Plasma
=
// Control_Technology.No_Change
0, // Fac_CT_Cost.High
0, // Fac_CT_Cost.Medium
0, // Fac_CT_Cost.Low
// Control_Technology.Sorbent_Bed
*, // Fac_CT_Cost.High
*, // Fac_CT_Cost.Medium
*, // Fac_CT_Cost.Low
// Control_Technology.Pulsed_Plasma
*, // Fac_CT_Cost.High
*, // Fac_CT_Cost.Medium
*, // Fac_CT_Cost.Low
chance O_M_CT_Cost_Baseline_{High,Medim,Low}|Control_Technology=
{1.00,0,0}, // Control_Technology.No_Change
triangular(17600,70600,35300), // Control_Technology.Sorbent_Bed
triangular(4400,17700,8800), // Control_Technology.Pulsed_Plasma
=
// Control_Technology.No_Change
0, // O_M_CT_Cost_Baseline_High
0, // O_M_CT_Cost_Baseline_Medim

```

```

0, // O_M_CT_Cost_Baseline_.Low
// Control_Technology.Sorbent_Bed
*, // O_M_CT_Cost_Baseline_.High
*, // O_M_CT_Cost_Baseline_.Medim
*, // O_M_CT_Cost_Baseline_.Low
// Control_Technology.Pulsed_Plasma
*, // O_M_CT_Cost_Baseline_.High
*, // O_M_CT_Cost_Baseline_.Medim
*, // O_M_CT_Cost_Baseline_.Low
value EP_Fuel_Impact|Fuel_Type=
100, // Fuel_Type.JP_8
99; // Fuel_Type.Additive
value EP_EM_Impact|Engine_Modifications=
100, // Engine_Modifications.No_Change
98, // Engine_Modifications.Modify_Engine
100; // Engine_Modifications.New_Engine
value OOC_Fuel_Impact|Fuel_Type=
100, // Fuel_Type.JP_8
99; // Fuel_Type.Additive
value OOC_EM_Impact|Engine_Modifications=
100, // Engine_Modifications.No_Change
98, // Engine_Modifications.Modify_Engine
100; // Engine_Modifications.New_Engine
value Back_Pressure|Control_Technology=
0, // Control_Technology.No_Change
0.66, // Control_Technology.Sorbent_Bed
0.5; // Control_Technology.Pulsed_Plasma
value OTF_Fuel_Impact|Fuel_Type=
100, // Fuel_Type.JP_8
100; // Fuel_Type.Additive
value OTF_CT_Impact|Control_Technology=
100, // Control_Technology.No_Change
99, // Control_Technology.Sorbent_Bed
98; // Control_Technology.Pulsed_Plasma
value NOx_Fuel_Impact|Fuel_Type=
0.00, // Fuel_Type.JP_8
0.05; // Fuel_Type.Additive
value NOx_EM_Impact|Engine_Modifications=
0.00, // Engine_Modifications.No_Change
0.35, // Engine_Modifications.Modify_Engine
0.40; // Engine_Modifications.New_Engine
value NOx_CT_Impact|Control_Technology=
0.00, // Control_Technology.No_Change
0.55, // Control_Technology.Sorbent_Bed
0.85; // Control_Technology.Pulsed_Plasma
value CO_Fuel_Impact|Fuel_Type=
0.00, // Fuel_Type.JP_8
0.05; // Fuel_Type.Additive
value CO_EM_Impact|Engine_Modifications=
0.00, // Engine_Modifications.No_Change
0.03, // Engine_Modifications.Modify_Engine
0.05; // Engine_Modifications.New_Engine
value SO2_Fuel_Impact|Fuel_Type=
0.00, // Fuel_Type.JP_8

```

```

0.00; // Fuel_Type.Additive
value SO2_EM_Impact|Engine_Modifications=
0.00, // Engine_Modifications.No_Change
0.00, // Engine_Modifications.Modify_Engine
0.00; // Engine_Modifications.New_Engine
value SO2_CT_Impact|Control_Technology=
0.00, // Control_Technology.No_Change
0.55, // Control_Technology.Sorbent_Bed
0.45; // Control_Technology.Pulsed_Plasma
value PM_Fuel_Impact|Fuel_Type=
0.00, // Fuel_Type.JP_8
0.05; // Fuel_Type.Additive
value PM_EM_Impact|Engine_Modifications=
0.00, // Engine_Modifications.No_Change
0.03, // Engine_Modifications.Modify_Engine
0.05; // Engine_Modifications.New_Engine
value PM_CT_Impact|Control_Technology=
0.00, // Control_Technology.No_Change
0.55, // Control_Technology.Sorbent_Bed
0.45; // Control_Technology.Pulsed_Plasma
value R_D_Fuel_Cost|Fuel_Type=
0, // Fuel_Type.JP_8
225000; // Fuel_Type.Additive
value Acq_Fuel_Cost|Fuel_Type=
0, // Fuel_Type.JP_8
12000; // Fuel_Type.Additive
value Acq_CT_Cost|Control_Technology=
0, // Control_Technology.No_Change
150000, // Control_Technology.Sorbent_Bed
200000; // Control_Technology.Pulsed_Plasma
value Fac_Fuel_Cost|Fuel_Type=
0, // Fuel_Type.JP_8
0; // Fuel_Type.Additive
value O_M_Fuel_Cost|Fuel_Type=
0, // Fuel_Type.JP_8
935000; // Fuel_Type.Additive
value O_M_EM_Cost|Engine_Modifications=
0, // Engine_Modifications.No_Change
0, // Engine_Modifications.Modify_Engine
0; // Engine_Modifications.New_Engine
value Imp_Fuel_Time|Fuel_Type=
0, // Fuel_Type.JP_8
4; // Fuel_Type.Additive
value Imp_EM_Time|Engine_Modifications=
0, // Engine_Modifications.No_Change
6, // Engine_Modifications.Modify_Engine
3; // Engine_Modifications.New_Engine
value Imp_CT_Time|Control_Technology=
0, // Control_Technology.No_Change
2, // Control_Technology.Sorbent_Bed
2; // Control_Technology.Pulsed_Plasma
value R_D_Fuel_Time|Fuel_Type=
0, // Fuel_Type.JP_8
3; // Fuel_Type.Additive

```

```

value R_D_EM_Time|Engine_Modifications=
    0, // Engine_Modifications.No_Change
    3, // Engine_Modifications.Modify_Engine
    3; // Engine_Modifications.New_Engine
value R_D_CT_Time|Control_Technology=
    0, // Control_Technology.No_Change
    1, // Control_Technology.Sorbent_Bed
    3; // Control_Technology.Pulsed_Plasma
value Backpressure_Threshold=@if(Back_Pressure>1,0,1);
value UHC_Fuel_Impact|Fuel_Type=
    0.00, // Fuel_Type.JP_8
    0.05; // Fuel_Type.Additive
value UHC_EM_Impact|Engine_Modifications=
    0.00, // Engine_Modifications.No_Change
    0.03, // Engine_Modifications.Modify_Engine
    0.05; // Engine_Modifications.New_Engine
value UHC_CT_Impact|Control_Technology=
    0.00, // Control_Technology.No_Change
    0.25, // Control_Technology.Sorbent_Bed
    0.65; // Control_Technology.Pulsed_Plasma
value UHC=UHC_Fuel_Impact+UHC_EM_Impact*(1-UHC_Fuel_Impact)+UHC_CT_Impact*
    (1-(UHC_Fuel_Impact+UHC_EM_Impact*(1-UHC_Fuel_Impact)));
value Annual_R_D_Fuel_Cost=@if(R_D_Fuel_Time==0,R_D_Fuel_Cost,
    R_D_Fuel_Cost/R_D_Fuel_Time);
value Annual_R_D_EM_Cost=@if(R_D_EM_Time==0,R_D_EM_Cost,R_D_EM_Cost/R_D_EM_Time);
value Annual_R_D_CT_Cost=@if(R_D_CT_Time==0,R_D_CT_Cost,R_D_CT_Cost/R_D_CT_Time);
value Annual_Acq_Fuel_Cost=@if(Imp_Fuel_Time==0,Acq_Fuel_Cost,Acq_Fuel_Cost/Imp_Fuel_Time);
value Annual_Acq_EM_Cost=@if(Imp_EM_Time==0,Acq_EM_Cost,Acq_EM_Cost/Imp_EM_Time);
value Annual_Acq_CT_Cost=@if(Imp_CT_Time==0,Acq_CT_Cost,Acq_CT_Cost/Imp_CT_Time);
value Annual_Fac_Fuel_Cost=@if(Imp_Fuel_Time==0,Fac_Fuel_Cost,Fac_Fuel_Cost/Imp_Fuel_Time);
value Annual_Fac_CT_Cost=@if(Imp_CT_Time==0,Fac_CT_Cost,Fac_CT_Cost/Imp_CT_Time);
value Annual_O_M_CT_Cost=O_M_CT_Cost_Baseline*(1-NOx_Fuel_Impact)*(1-NOx_EM_Impact);
value Annual_O_M_Fuel_Cost=O_M_Fuel_Cost;
value Annual_O_M_EM_Cost=O_M_EM_Cost;
value Time=@max(R_D_Fuel_Time+Imp_Fuel_Time,R_D_EM_Time+
    Imp_EM_Time,R_D_CT_Time+Imp_CT_Time);
value Engine_Performance=(EP_Fuel_Impact)*(EP_EM_Impact)/100;
value Other_Operational_Considerations=(OOC_Fuel_Impact)*(OOC_EM_Impact)/100;
value Back_Pressure_Score=@if(Back_Pressure>1,0,(-0.05*Back_Pressure+1)*100);
value Other_Testing_Factors=(OTF_Fuel_Impact)*(OTF_CT_Impact)/100;
value NOx=NOx_Fuel_Impact+NOx_EM_Impact*(1-NOx_Fuel_Impact)+
    Nox_CT_Impact*(1-(NOx_Fuel_Impact+NOx_EM_Impact*(1-NOx_Fuel_Impact)));
value CO=CO_Fuel_Impact+CO_EM_Impact*(1-CO_Fuel_Impact)+
    CO_CT_Impact*(1-(CO_Fuel_Impact+CO_EM_Impact*(1-CO_Fuel_Impact)));
value SO2=SO2_Fuel_Impact+SO2_EM_Impact*(1-SO2_Fuel_Impact)+
    SO2_CT_Impact*(1-(SO2_Fuel_Impact+SO2_EM_Impact*(1-SO2_Fuel_Impact)));
value PM=PM_Fuel_Impact+PM_EM_Impact*(1-PM_Fuel_Impact)+
    PM_CT_Impact*(1-(PM_Fuel_Impact+PM_EM_Impact*(1-PM_Fuel_Impact)));
value R_D_Cost=@pv(Annual_R_D_Fuel_Cost,Interest_Rate,R_D_Fuel_Time)+
    @pv(Annual_R_D_EM_Cost,Interest_Rate,R_D_EM_Time)+
    @pv(Annual_R_D_CT_Cost,Interest_Rate,R_D_CT_Time);
value Acquisition_Cost=(@pv(Annual_Acq_Fuel_Cost,Interest_Rate,Imp_Fuel_Time)*
    (1+Interest_Rate)^(-R_D_Fuel_Time))+(@pv(Annual_Acq_EM_Cost,Interest_Rate,
    Imp_EM_Time)*(1+Interest_Rate)^(-R_D_EM_Time))+(@pv(Annual_Acq_CT_Cost,

```

```

Interest_Rate,Imp_CT_Time)*(1+Interest_Rate)^(-R_D_CT_Time));
value Facility_Cost=(@pv(Fac_Fuel_Cost,Interest_Rate,Imp_Fuel_Time)*(1+Interest_Rate)
^(-R_D_Fuel_Time))+(@pv(Fac_CT_Cost,Interest_Rate,Imp_CT_Time)*(1+Interest_Rate)
^(-R_D_CT_Time));
value O_M_Cost=(@pv(Annual_O_M_Fuel_Cost,Interest_Rate,(Time_Horizon-
R_D_Fuel_Time-Imp_Fuel_Time))*(1+Interest_Rate)^(-R_D_Fuel_Time-Imp_Fuel_Time))+
(@pv(Annual_O_M_EM_Cost,Interest_Rate,(Time_Horizon-R_D_EM_Time-Imp_EM_Time))*
(1+Interest_Rate)^(-R_D_EM_Time-Imp_EM_Time))+(@pv(Annual_O_M_CT_Cost,
Interest_Rate,(Time_Horizon-R_D_CT_Time-Imp_CT_Time))*(1+Interest_Rate)^
(-R_D_CT_Time-Imp_CT_Time));
value NOx_Threshold=@if(NOx<0.10,0,1);
value CO_Threshold=@if(CO<0.10,0,1);
value Cost=R_D_Cost+Acquisition_Cost+Facility_Cost+O_M_Cost;
value Environmental_Compliance_Score=(W1)*(NOx)+(W2)*(CO)+(W3)*(UHC)+(W4)*(SO2)+
(W5)*(PM);
value Test_Performance=(Other_Testing_Factors)*(Back_Pressure_Score)/100;
value Utility=(NOx_Threshold*CO_Threshold)*(Environmental_Compliance_Score);
value Operational_Impact_Score=Backpressure_Threshold*(EP_Weight*Engine_Performance+
OOC_Weight*Other_Operational_Considerations+TP_Weight*Test_Performance);

```

```

sequence( attributes = 4,
objective = @if($2>98,$1,0) );

```

```

set Fuel_Type.JP_8 then
// options for Fuel_Type = {JP_8, Additive}
set Engine_Modifications.New_Engine then
// options for Engine_Modifications = {No_Change,Modify_Engine,New_Engine}
decide to Control_Technology then
gamble on R_D_EM_Cost then
gamble on R_D_CT_Cost then
gamble on Acq_EM_Cost then
gamble on Fac_CT_Cost then
gamble on O_M_CT_Cost_Baseline_then
gamble on CO_CT_Impact and get Utility, Operational_Impact_Score, Cost, Time

```


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Vita

Captain Jeffrey R. Ullmann was born on 30 August 1968 in La Mirada, California. After spending his childhood in Orange County, California, he graduated from Servite High School in 1986 and entered undergraduate studies at the University of Southern California. He earned a Bachelor of Science degree in Electrical Engineering from the University and was commissioned a Second Lieutenant through the Reserve Officer Training Corps, Detachment 60, on 10 May 1990. His first assignment was to Sheppard AFB, Texas. While there, he served as the Work Information Management Systems Program Manager and as a project engineer in the maintenance engineering section of the 82d Civil Engineer Squadron, Operations Flight. During the spring and summer of 1994, he deployed to Incirlik Air Base, Turkey as the team chief of a 50-person civil engineer Prime BEEF team to support OPERATION PROVIDE COMFORT. In May 1994, he entered the Engineering and Environmental Management Program, Graduate School of Engineering, Air Force Institute of Technology. Following graduation, Captain Ullmann will accept an assignment to the 81st Civil Engineer Squadron, Keesler AFB, Mississippi.

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