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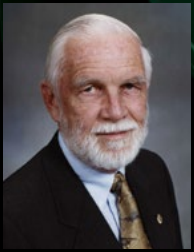
Performance Benefits of Intercooling



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Gas turbine intercooling is the removal of heat from gas path flow during compression, thereby reducing compressor work. It can be achieved commonly by the use of an heat exchanger (the intercooler) mounted between the low and high compressors [1] or between any two stages of gas path compression [2].

Because of the cost and complexity of adding an intercooler, usually no more than one is used. Best performance occurs when the pressure ratio of both high and low compressors are the same which dictates that the high compressor inlet temperature is the same as the inlet temperature of the low compressor [3], for ideal operation of the intercooler.

In recent years, gas turbine designers have found various ways to use intercooling to not only reduce compressor work, but to also provide the means of increasing engine thermal efficiency for marine and land-based gas turbines. Recent studies show that if intercooler weight and size can be optimized, their use in turbojet engines could be beneficial.

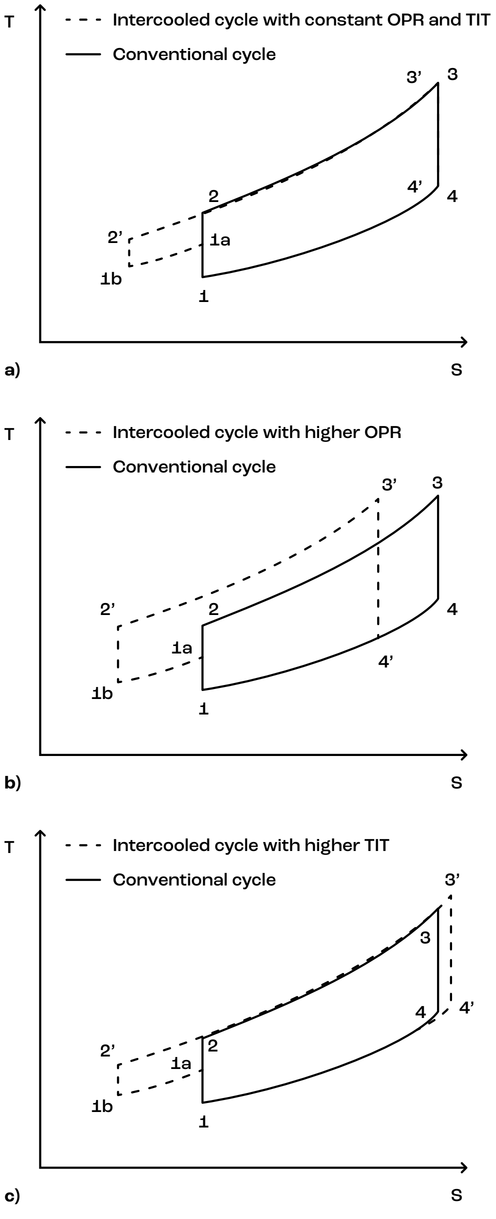

Figure 1. Conventional Brayton cycle with various intercooled configurations on Temperature(T)/Entropy(s) plots (Zhao [4]). OPR-Overall Pressure Ratio; TIT-Turbine Inlet Temperature

Parameters for Intercooling

In many gas turbine [3] and thermodynamic textbooks, intercooling is introduced as a way to reduce compressor work, which increases gas turbine specific work. The temperature-entropy (T-S) diagram in Fig. 1(a) [4] shows an ideal Brayton cycle, 1-2-3-4, where intercooling is introduced at 1a-1b-2’-2. This is the usual textbook intercooling example, holding the overall pressure ratio (OPR) and the turbine inlet temperature (TIT) constant, to achieve reduced compressor work. The resulting cycle thermal efficiency is thus reduced, scaled by the extent of heat removed by the intercooler 1a-1b, to maintain the same OPR and TIT. (Also, since the ratio of the area enclosed by the cyclic curve to the area under the heat addition curve represents the cycle thermal efficiency, comparison of the ratio for 1-2-3-4 to that of 1-1a-1b-2’-2-3’-4’ in Fig. 1(a), confirms the intercooling reduction in thermal efficiency.)

Figure 1(b) [4] is a T-S diagram for the same ideal Brayton cycle, 1-2-3-4, where intercooling is introduced, and a higher OPR is set. This forms the higher thermal efficiency cycle with the increased OPR at 1-1a-1b-2’-3’-4’, as shown in Fig. 1(b).

Similarly, as shown by the T-S diagram in Fig. 1(c) [4], for the case of increased TIT, intercooling lowers the high compressor exit gas temperatures. This provides colder turbine cooling air, allowing for the increased TIT, buttressed by more effective turbine cooling. The lowered high compressor gas temperatures also allow the last stages of the high compressor to avoid high temperature stresses at the higher TIT, as well as lowering compressor work required.

Intercooling Yields Most Efficient Gas Turbine

In December 2003, General Electric introduced their intercooled 100 MW-class LMS100 electric power gas turbine, hailing it [1] as the most efficient gas turbine. Through the use of intercooling technology, GE announced that the LMS100 reached a simple cycle efficiency of 46%, some 10% greater than their then record holding LM6000 gas turbine, and setting a world record for simple cycle gas turbines.

As shown in Fig. 2, the LMS100 (Land-Marine-Supercharged) unit is a three-spool gas turbine combining frame (MS6001FA) and aeroderivative (CF6-80) gas turbine technology. It is aimed at the mid-merit and daily cycling segments of the electric power market - the difficult-to-predict, must-be-ready-to start electrical peak and intermediary power providers. Current industry sources indicate that since 2006, about 80 LMS100 units have been installed worldwide, with many of them in North America.

Earlier, I wrote [5] about LMS100 Unit 14 which went into service in 2009, at Waterbury, Connecticut, fueled by natural gas, with low sulfur distillate as a backup. At 100 MW the Waterbury power plant is not large, but the unique intercooler is. Shipped from its manufacturing site in Korea, the air-to-water intercooler was barged up the Connecticut River. Then the 225,000-pound cylindrical heat exchanger, at about half the length of the gas turbine unit, was transported overland to Waterbury at 6 mph on a 96-wheel trailer truck.

Intercooling in Turbojets

The LMS100 is an outstanding example of the use of an intercooler to improve gas turbine thermal efficiency. However, it is a land-based gas turbine where weight and size of the intercooler are not primary concerns.

Such is not the case of intercooler use in a jet engine for flight propulsion. As Zhao [4] and others have pointed out, it is important to achieve a light weight, compact intercooler design for a turbojet application. Increased engine weight would offset gains in intercooler derived fuel economy. The intercooler installation raises the prospect of increased engine volume, leading to more nacelle drag and the difficulty of fitting the intercooler as an effective heat exchanger into confined engine space.

Many of the recent jet engine intercooler studies in the literature I have seen, call upon the research carried out at Stanford University on compact heat exchangers by professors Kays and London [6]. My 1960s graduate studies at Stanford under the two faculty authors, show that using compact heat exchange technology for successful jet engine intercooler design will be challenging. If the challenges can be met, successful intercooled jet engines, akin to the outstanding LMS100, could be in our future.

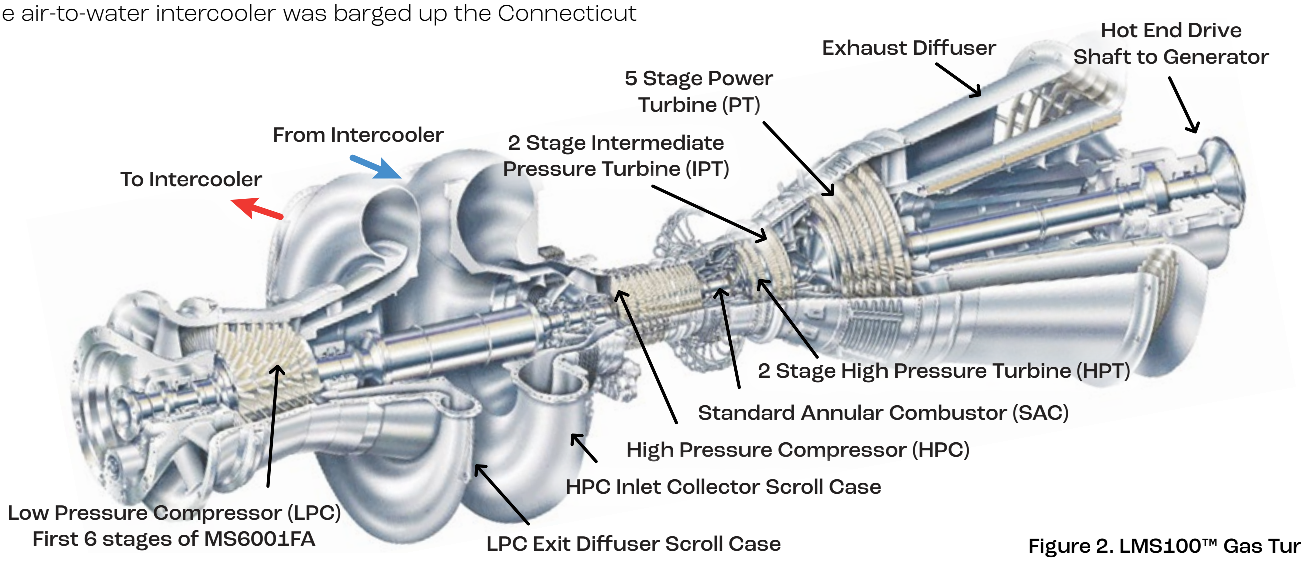

Figure 2. LMS100™ Gas Turbine

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Aviation Fleet Management: Transformation Through AI / Machine Learning

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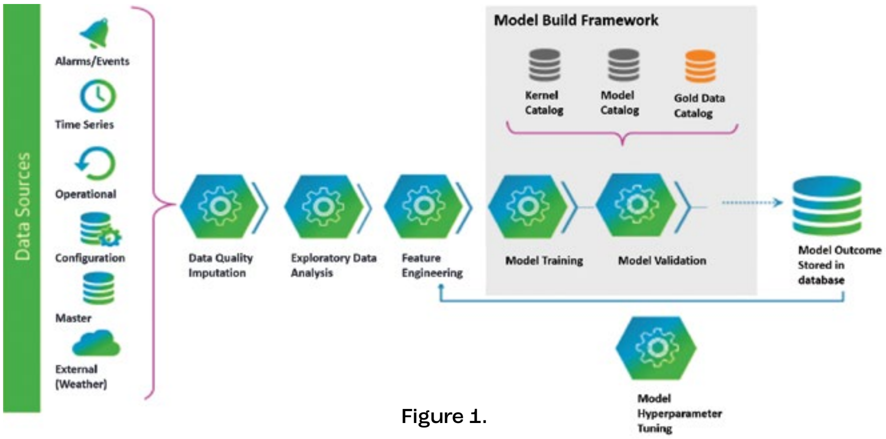


Figure 1.

The application of Artificial Intelligence (AI) and Machine Learning (ML) technologies for health monitoring of aircraft components and propulsion systems is pushing the envelope of Prognostics and Health Management (PHM) capabilities and changing the way PHM has traditionally been viewed.

Engine health monitoring has been in place for more than two decades. The key things that changed in the last decade are the data revolution and the platforms to harness the variety of data sources. This naturally led to an explosion in the digital transformation domain as companies attempted to realize the value of their data through initiatives and analytics. With terms such as Digital Twin, Internet of Things (IOT), Data Analytics, Industrial Internet, and Artificial intelligence (AI), more companies have begun to take up the banner of applying these to the core of their business. Alongside these initiatives are the expansion of groups and companies providing support for these major industrial applications in the area of digital and analytics.[1,2]

Artificial Intelligence and Machine Learning Framework for Digital-Twin Based Health Monitoring

Digital twin can be defined as a collection of digital data that represents certain characteristics of a physical object, system, or real-world process. When expanded to combine models with data, a digital twin can also capture the behaviors of the real-world physical asset.

The idea of a digital twin is well-known at the consumer level. Amazon has a digital twin of each of their customers, which includes demographics, preferences and appetites, past purchases, shopping behavior, and so on. This idea can be applied to physical assets such as airplanes, aircraft engines, manufacturing processes and supply chains, and financial systems, to name just a few.

The concept of digital twin can be applied iteratively at the level of a component, sub-system, or system. A digital twin can even be a collection of lower-level digital twins. In this manner, a digital twin of an aircraft may comprise data and models at the vehicle level, along with digital twins of the airframe, engines, APU, landing gear, etc. Similarly, this aircraft digital twin may be one member of a virtual fleet of aircraft digital twins that are part of a higher-order airline operation digital twin. These twins unlock significant value when both a physics-based understanding and data driven technologies such as AI/ML are fused together. Figure 1 illustrates a framework to build these twins.

The following aspects need to be considered as part of this framework.

Data Exploration:

Data exploration is a key step in building any AI/ML models. It's very important to look at the problem from a higher dimension and ensure that all possible data sources are considered as inputs to this exercise.

Feature Engineering:

This is a key step in fusing the domain knowledge with data driven insights. Statistical and machine learning techniques coupled with domain knowledge are applied to select the key data sources or data segments that help in understanding or segregating the problem. These engineered features are input to the AI/ML driven digital twin model. The quality of these features determines the efficacy and validity of the final AI/ML.

Model Building and Validation:

By the nature of jet engine operations, the problems we encounter are "class imbalance" problems (i.e., the total number of problem instances is far less than the total number of healthy instances). This requires a special attention and care while building these ML/AI models in order to avoid over fitting and aid the explainability of these models.

Advanced machine learning model selection is dependent on the type of the problem and business outcome desired. Examples of desired business outcomes are:

- Tell me when Asset XYZ is 5 days away from failure
- Tell me when Asset XYZ is below X% risk of failure in the next Y days
- Alert me when Asset XYZ has an indication that correlates to "a" problem
- Alert me when Asset XYZ is behaving differently compared to other assets in its class

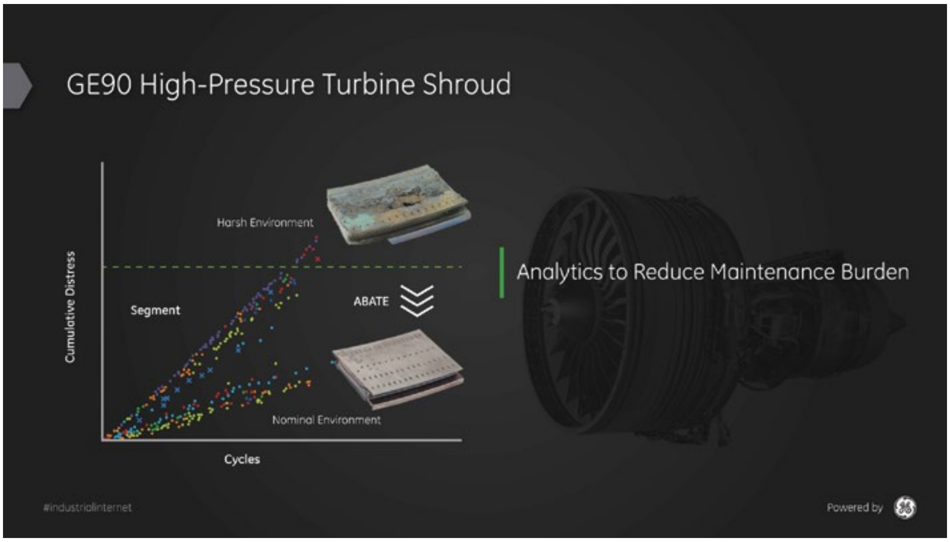
The above framework is being applied to solve many problems at GE Aviation, and an example is illustrated in Figure 2.

These digital twins are built at the asset-by-asset (component) level, capturing the variations from operations and environmental parameters. This level of knowledge extraction and sophistication helped to achieve the following outcomes for a middle east operator using analytics and platform .

- 56% decrease in disruptions
- 15% decrease in overhauls
- 12 additional days of utilization per year

Conclusions and Future Direction

Aviation industry is applying AI and ML to all areas of its business. The application of these revolutionary digital technologies is a "multi-disciplinary sport". Players from different parts of an organization (customer, digital, engineering and business/product management etc.) need to come together to drive differentiated outcomes. The experts are projecting an increase in the application of AI/ML in all aspects of the Aviation business. A significant, and still largely unrealized benefit of a digital twin has the potential to be utilized for multiple outcomes. For example, the same digital twin could be used to assess the current health and deterioration state of an asset for scheduling maintenance; to forecast the remaining useful life under current operating conditions for planning shop visit schedules; to estimate the future state of health for work scope planning and MRO inventory management; and finally, to optimize the design of product improvements and future products by virtually testing the impact of design decisions. The future of Aviation fleet management is set to witness a huge transformation with the advent of AI/ML technologies.


GE90 High-Pressure Turbine Shroud

Analytics to Reduce Maintenance Burden

Figure 2. Framework application example.

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Ammonia as Jet Fuel: One Path to Zero-Carbon Aviation

Lance L. Smith, Technical Fellow, Raytheon Technologies Research Center

In November 1960, long before global warming was a concern, an ammonia-fueled rocket plane propelled itself through the sky above the California desert leaving behind only a trail of water vapor and some extra nitrogen. Sixty years later that first flight of NASA's ammonia-powered X-15 airplane has new significance: it was a demonstration not only of speed, but of carbon-free flight.

In recent years hydrogen has received significant attention as a "green" fuel, but the X-15 serves as a reminder that ammonia has unique advantages which are worth revisiting. Like hydrogen, ammonia is carbon-free. Unlike hydrogen, ammonia can be stored as a liquid at non-cryogenic temperatures, and it has an existing worldwide infrastructure for transport and handling[1]. Furthermore, it was chosen for the X-15 in part because ammonia exhibits excellent heat-transfer properties that are valuable in both rocket and gas-turbine applications. For these reasons, ammonia is now being evaluated as a carbon-free fuel for commercial aviation under an ARPA-E program at Raytheon Technologies [2]. These evaluations are especially focused on the unique efficiency improvements offered by ammonia's physical properties, which help to offset ammonia's heavier weight as a fuel compared to Jet fuel (lower heating value of 18.6 MJ/kg for ammonia, versus 43 MJ/kg for Jet fuel).

Combustion of Ammonia

Although typically thought of as a fertilizer or refrigerant, ammonia is in fact an energetic fuel. When combusted in oxygen or air, ammonia's heat-release (ΔH) per mole of oxygen consumed is similar to a hydrocarbon fuel, so ammonia's flame temperature (T_{flame}) is also similar to a hydrocarbon fuel[3]. For comparison, the overall combustion reactions of ammonia versus methane (the simplest hydrocarbon) in oxygen are written below, along with their corresponding values for ΔH and T_{flame}:

$$Ammonia\ (NH_3):\quad O_2 + \frac{4}{3}NH_3 \rightarrow 2H_2O + \frac{2}{3}N_2$$

$$\Delta H = -422\frac{kJ}{mol_{O_2}}, T_{flame\ in\ air} = 1800°C$$

$$Methane\ (CH_4):\quad O_2 + \frac{1}{2}CH_4 \rightarrow H_2O + \frac{1}{2}CO_2$$

$$\Delta H = -401\frac{kJ}{mol_{O_2}}, T_{flame\ in\ air} = 1950°C$$

The above chemical equations highlight the motivating difference between these fuels: only the hydrocarbon fuel produces CO_2 as a product of combustion; in contrast, ammonia's products of combustion are water and nitrogen, H_2O and N_2. An important practical difference between these fuels, which is not evident from the overall chemical equations, is that their rates of combustion (or flame speeds) are very different. The laminar flame speed for most hydrocarbon fuels is roughly 40 cm/s (at ambient, stoichiometric burning conditions), as compared to a much slower 7 cm/s for ammonia[3]. Ammonia can burn, but it doesn't burn as well as conventional fuels. For this reason, the combustion properties of ammonia are also being studied at Raytheon Technologies, under a DOE program to evaluate ammonia combustion in power-generating gas turbines[4].

One way to aid the combustion of ammonia is to co-fire it with another fuel such as natural gas or kerosene[5], or hydrogen. If hydrogen is used, it can be obtained directly from the ammonia fuel itself before combustion, by catalytically cracking a portion (or all) of the ammonia:

$$Catalytic\ Cracking:\quad 2NH_3 \xrightarrow{catalyst} N_2 + 3H_2$$

$$\Delta H = +2.7\ {}^{MJ}/_{kg_{NH_3}}$$

Initial studies indicate that Jet-fuel-like combustion properties, especially flame speeds, can be obtained for a fuel composition comprising only about 5% hydrogen by weight[3].

The cracking of ammonia fuel can also provide an efficiency benefit, if a higher percentage of it is cracked. Because ammonia cracking is endothermic, the energy content of the cracked fuel (H_2 and N_2) is about 15% higher than the ammonia from which it came. For an engine (thermodynamic cycle) this opens up the possibility of "chemical recuperation" by using exhaust waste heat (after all work extraction) to drive the cracking reactions, thus recapturing what would have been lost heat energy by converting it to fuel energy that is returned to the highest-temperature point of the cycle, at the engine's combustor. In addition to this chemical recuperation effect, simply heating the fuel to raise its temperature can also return waste-heat to the highest-temperature point of the cycle, and can provide additional efficiency gains. Ammonia is especially well suited to heating because unlike hydrocarbon fuels, which form carbonaceous deposits or "coke" when exposed to high temperatures, ammonia can be heated from its low storage temperature (e.g. -33°C for liquefaction, or colder at cruise altitude) to the temperature of any heat source (e.g. jet engine exhaust at ~300 – 500 °C), absorbing significant energy and enabling recovery of some of the work required for its liquefaction. As a result, exhaust-heat recapture to the fuel can provide well over 15% efficiency gain in an ammonia-fueled engine.

Ammonia as a Working Fluid

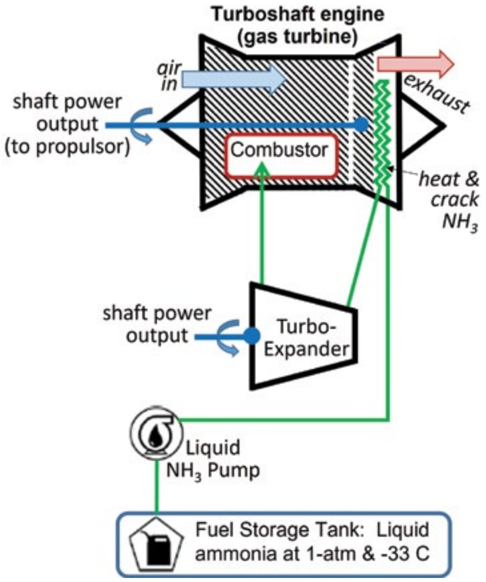
For ground-based gas turbines, such as those studied under the DOE ammonia combustion project, exhaust waste-heat is often recaptured in a bottoming cycle that uses water as the working fluid: in these systems, ammonia cracking is a useful tool for improving combustor performance, but is not necessary to achieve high efficiency. For an aircraft gas turbine, however, it is preferable to use the fuel itself as a working fluid for heat recapture, avoiding the undesirable weight of a water system. Because ammonia does not coke, and because it has favorable physical properties for heat transfer and phase change, it is an ideal working fluid for this purpose – see Table 1 below and compare ammonia's conductivity, heat capacity, and heat of vaporization to water or Jet fuel. In addition to having favorable properties, because the ammonia fuel is consumed in the engine (and not returned to the storage tank) its use as a working fluid enables an open bottoming cycle that does not need a cooling heat exchanger. This avoids the weight and drag penalties associated with such a heat exchanger, and makes this type of fuel-based bottoming cycle especially attractive for an aircraft engine.

By making simultaneous use of ammonia's capabilities as a fuel, a heat absorber, and a working fluid with favorable phase-change properties, ammonia can be used in a combined-cycle heat engine that converts waste-heat to useful work in at least three distinct and complementary ways: i. chemical recuperation, by cracking ammonia to increase the fuel's energy before burning; ii. fuel heating, to bring more thermal energy to the combustor; and iii. bottoming-cycle work generation, using ammonia as a Rankine cycle working fluid. Figure 1 illustrates an ammonia-fueled propulsion engine cycle that uses all three methods, and which we are currently studying under our ARPA-E project. In this ARPA-E propulsion engine the ammonia fuel system comprises an open Rankine bottoming cycle wherein ammonia, from its stored liquid state, is pumped to high pressure before entering a heat exchanger in the gas turbine's exhaust. The exhaust waste-heat raises the ammonia temperature above its critical value, bringing it to a gaseous state for subsequent turboexpansion (work extraction) and catalytic cracking. The heated, cracked ammonia is then delivered to the gas turbine's combustor as its fuel. Key technology development for this project includes ammonia cracking at high pressure (above combustor pressure), ammonia turboexpander operation, ammonia combustion, and cycle optimization to achieve thermal efficiencies approaching 70% at cruise, where most of the aircraft's fuel is consumed and efficiency improvements provide the most benefit.

Table 1: Comparison of Working Fluid Properties

Thermal Property	NH_3 - anhydrous (-33°C liquid)	H_2O (ambient liquid)	Jet-A (ambient liquid)
Conductivity, k (W/m-k)	0.6 W/m-K	0.6 W/m-K	0.1 W/m-K
Heat Capacity, Cp (kJ/kg-K)	4.5 kJ/kg-K	4.2 kJ/kg-K	2.0 kJ/kg-K
Heat of Vaporization, h_fg (kJ/kg)	1360 kJ/kg	2260 kJ/kg	350 kJ/kg
Heat of Cracking reaction (kJ/kg)	2700 kJ/kg	N/A	coking issue

Figure 1. Ammonia-fueled aircraft propulsion engine, using ammonia as the working fluid to recapture exhaust-heat to an open Rankine bottoming cycle and to endothermic cracking, with resulting overall efficiencies near 70% for reduced aircraft fuel burn and zero CO_2 emissions.



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