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U.S. ARMY QUALIFICATION OF ALTERNATIVE FUELS SPECIFIED IN MIL-DTL-83133H FOR GROUND SYSTEMS USE

Final Qualification Report: JP-8 Containing Synthetic Paraffinic Kerosene
Manufactured Via Fischer-Tropsch Synthesis or Hydroprocessed Esters and Fatty Acids

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EXECUTIVE SUMMARY

Purpose

The Fuels and Lubricants Technology Team (FLTT) is leading the Tank Automotive Research, Development, and Engineering Center (TARDEC) program to qualify alternative fuels for use in military ground systems. These systems include tactical and combat ground vehicles, tactical generator sets, and other tactical ground systems. This is the first comprehensive report that summarizes the initial project under this program to concurrently qualify two alternative fuels. These fuels, designated in MIL-DTL-83133H, are both blends of JP-8 refined from conventional feedstocks with up to 50% by volume of Synthetic Paraffinic Kerosene (SPK). SPK consists of a distribution of synthetically-derived hydrocarbon molecules that together have the right balance of properties to result in an aviation-grade SPK. The naming of the two SPK blending stocks is drawn from a significant aspect of the unique processes by which they are manufactured; one blending stock is known as Fischer-Tropsch (FT) SPK and the other is known as Hydroprocessed Esters and Fatty Acids (HEFA) SPK.

Importance of Project

This project conducted evaluations to determine the suitability for use in military ground systems of FT SPK blends (with petroleum JP-8) and HEFA SPK blends (with petroleum JP-8) as replacements to conventional JP-8. Department of Defense (DoD) policy dictates the use of JP-8 or JP-5, which is essentially a high flashpoint version of JP-8, as the primary fuel for land-based air and ground forces in all theaters. Therefore, JP-8/JP-5 is the predominate fuel used by the Army, Air Force, and Marine Corps, and Navy (JP-5) for onboard ship use to support naval aircraft at sea. Although qualification of these blends is shaped by Service-unique platforms and equipment that operate on JP-8/JP-5, the Service qualification efforts are coordinated through the Tri-Service Petroleum, Oil, and Lubricants (POL) Users Group to minimize redundancy and share results. If the TARDEC qualification project determines that these blends are suitable as drop-in replacements for JP-8, these blends will be approved for military ground systems use by means of a modification to the JP-8 specification MIL-DTL-83133; a modification that removes the clause that restricts such use without permission of the procuring activity and the applicable fuel technical authority listed.

Approach

This project has evaluated the SPK blends (with petroleum JP-8) through Technology Readiness Level (TRL) 7 to qualify them for use in military ground systems. TRL 1-4 evaluations focus on the chemical and physical properties of the SPK blends, their material compatibility, and their environmental and health impacts. The Army has leveraged a significant body of knowledge from TRL 1-4 evaluations conducted by the Air Force, Navy, as well as commercial aviation stakeholders engaged in the qualification and certification of alternative jet fuels since JP-8/JP-5 is based on commercial jet fuel containing mandatory, military-approved additives. TARDEC conducted extensive TRL 5-6 evaluations on the performance and durability of a variety of fuel injection systems and engines when operating on the SPK blends. The selected sub-systems represent a cross-section of the various technologies in the military ground fleet that store, handle, distribute, and/or consume fuel (JP-8 type). TARDEC conducted limited TRL 7 evaluations to assess and demonstrate the performance and operability of vehicles and equipment when operating on the SPK blends.

Results

TRL 1-4 evaluations established that the properties of SPK blends are very similar to conventional JP-8, as is their materials compatibility. TRL 1-4 evaluations also established that the properties of the FT SPK and HEFA SPK blendstocks were very similar to one another, and thus also the same of their blends with JP-8. Based on this latter fact, a concurrent qualification approach was adopted wherein TRL 5-7 evaluations could be conducted using either type of SPK blend, i.e., FT or HEFA. Additionally, TRL 1-4 evaluations established that while nearly all SPKs have relatively high cetane numbers (>45) indicating very good ignition and combustion characteristics for use in compression-ignition engines, there is one supplier that manufactures an SPK having a relatively low cetane number (<35). Based on this discovery, the Army sought and successfully achieved the inclusion of an additional requirement in the JP-8 specification to ensure that SPK blends will have acceptable cetane numbers (≥ 40). TRL 5-7 evaluations established that the performance and durability of military ground equipment when operating on the SPK blends is similar to when operating on JP-8. Based on the results of all TRL 1-7 evaluations, the SPK blends were found to be acceptable as drop-in fuels to replace petroleum JP-8.

Military Impact

DoD is highly dependent on energy dense liquid hydrocarbon fuels, such as jet fuel, for the operation of its air and ground platforms. In turn, DoD's operational energy supply is highly dependent on the global oil market and refining capacity to convert this oil into finished fuels. The DoD has recognized that operational energy supply is subject to supply-demand imbalances in the global oil market, and as a result DoD budgets are subject to the price escalations that result from supply shortfalls. There is also the recognition that DoD operational energy supply is vulnerable to unexpected disruptions that can occur because of geopolitical events, terrorist actions, or natural disasters that interrupt the normal movements of oil and operation of refineries. Through projects like this, that are qualifying and approving non-petroleum based fuels for military use, the military will be able to take advantage of more diverse energy supplies and thus enhance its energy security posture.

FOREWARD / ACKNOWLEDGMENTS

Many individuals, including some in organizations outside of TARDEC, made contributions to this qualification project. The full list of names is too numerous to list here. However, the names of several individuals are listed below to acknowledge the very significant contributions made by them. In addition, a special recognition goes to James S. Dusenbury, Ph.D., for his critical review of the report draft – many improvements were incorporated into the report based on his feedback.

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I. OBJECTIVE

The objective of this Final Qualification Report is to provide a comprehensive summary of the evaluations completed to establish the approval of two alternative fuels (blends of synthetic- and petroleum-derived hydrocarbons) specified in MIL-DTL-83133H¹ as drop-in fuels to replace petroleum JP-8 for ground systems use. In addition, this report provides background information for understanding why TARDEC conducted this alternative fuel qualification project.

II. BACKGROUND

Early Initiatives Within DoD and DOE

Interest in non-petroleum fuels is not new and this interest has been periodically re-invigorated during times when fuel prices have escalated or fluctuated dramatically. Many can recollect the Arab oil embargo in the early 1970s and the interest in the development of a U.S. synthetic fuels industry that ensued and then waned as fuel prices dropped to more historical norms. Near the advent of this millennium, the interest in less-polluting fuels ratcheted up because of more stringent environmental standards, and the Department of Energy (DOE) launched several initiatives to develop a new generation of ‘ultra-clean’ transportation fuels that included fuels from renewable sources, coal and natural gas. Improved energy security and U.S. competitiveness were also stated reasons for these DOE initiatives. In 2001, DOE funded one project to demonstrate synthetic fuels manufacturing technology employing Fischer-Tropsch (FT) synthesis at a plant in Oklahoma known as the Catoosa Demonstration Facility. This plant employed technology developed by Syntroleum Corporation, and they along with DOE and Marathon Oil also invested in its construction.

In 2002, Congress authorized funding for a defense-wide RDT&E program to develop a barge-mounted synthetic fuel production capability that would access and convert sources of off-shore natural gas into synthetic fuel. Syntroleum’s particular FT technology made such a production concept feasible. TARDEC became the lead for this program, run as an Advanced Concept Technology Demonstration (ACTD)-like program with oversight by the Deputy Under Secretary of Defense, Advanced Systems & Concepts (AS&C). As part of this program, TARDEC managed a DoD-DOE Joint Agency collaboration that commenced in 2003 to investigate the potential for synthetic fuels to be used by the military. A key objective of this collaboration was to define the FT fuel formulation, i.e., its specification, that would allow the use of the fuel in all DoD equipment. The collaboration team involved fuels experts from the DOE National Energy Technology Laboratory, the Air Force Research Laboratory, the Naval Air Systems Command Fuels & Lubricants Laboratory, and the TARDEC Fuels & Lubricants Laboratory, as well as nonprofit research partners and industry partner Syntroleum Corporation. The fuel for this investigative effort was supplied from the Catoosa Demonstration Plant. By 2005, this team had determined that an FT fuel formulation containing up to 50% by volume FT Synthetic Paraffinic Kerosene (SPK) and JP-8/JP-5 was an acceptable fuel formulation candidate for military use.

¹ Detail Specification, Turbine Fuel, Aviation, Kerosene Type, JP-8 (NATO F-34), NATO F-35, and JP-8+100 (NATO F-37), MIL-DTL-83133H, October 25, 2011.

Based on the promising early results from the Joint Agency team investigating the potential for synthetic fuel use by the military, the OSD (Office of the Secretary of Defense) Clean Fuels Initiative was launched in late 2004. By late 2005, the name was changed to the OSD Assured Fuels Initiative to emphasize its defense importance based on the recommendation of the Naval Research Advisory Committee. The vision of this initiative was “DoD/AT&L intends to catalyze commercial industry to produce clean fuels for the military from secure domestic resources using environmentally sensitive processes as a bridge to the future.” The on-going Army, Air Force, and Navy alternative fuel qualification and certification efforts can all trace their roots to these early initiatives within DoD and DOE.

Commercial Aviation Initiatives

In October of 2006, the Commercial Aviation Alternative Fuels Initiative (CAAFI) was launched that essentially mirrored the OSD Assured Fuels Initiative. This initiative “seeks to enhance energy security and environmental sustainability for aviation through alternative jet fuels.” CAAFI is also an instrumental coalition in fostering the development and commercialization of alternative jet fuels. The advancement of alternative jet fuels, especially for the U.S. market, has made much progress with the support of both commercial and military aviation fuel stakeholders. A significant result of this progress has been the development of modified jet fuel specifications. These modified specifications have enabled even more impressive results such as commercial flights on alternative jet fuels. In November 2011, Continental Airlines (subsidiary of United Continental Holdings) had the first domestic flight that carried passengers on an aircraft powered by an alternative jet fuel. The fuel was a blend of hydrocarbons derived from algal oil with conventional petroleum-based hydrocarbons. Also in November 2011, United Airlines announced it had signed a letter of intent for the purchase of 20 million gallons of alternative jet fuel annually, up to half of which (by volume) is made from algal oil, for delivery as early as 2014.

Following the CAAFI lead, a number of other initiatives to foster the commercialization of alternative jet fuels materialized. The Sustainable Aviation Fuels Northwest (SAFN) initiative was a stakeholder effort launched in July 2010 by Boeing, Alaska Airlines, Washington State University, and operators of the three largest regional airports. The study issued from this effort found that the U.S. northwest region has the diverse stocks, delivery infrastructure, and political will needed to establish a viable biofuels industry. Six months later, Alaska Airlines flew the first of 75 flights that were powered with a biofuel blend consisting of 20% by volume HEFA SPK and the balance petroleum jet fuel. These initiatives are not restricted to the U.S. alone as others have materialized in Europe, Australia, Brazil, and elsewhere.

“Drop-in” Fuels and Other Terminology

The research and development of alternative aviation fuels today involves a significant number of possible feedstocks and processes by which to convert them into suitable hydrocarbons. First and foremost, is the necessity that any alternative jet fuel must be “drop-in” suitable as a drop-in replacement, i.e., compatible with existing equipment, platforms, and infrastructure. This is an important requirement for commercial and military users because of the large number of existing aircraft as well as the pipelines, pumps and storage tanks that are needed to deliver the fuel to them. DoD and Army policy for operational fuels have been established primarily for the purpose of

commonality and standardization which are key elements underpinning logistics and sustainment philosophy. This policy is the Single Fuel on the Battlefield (SFB) Policy applying to all tactical, combat and weapons platforms including both air and ground systems. Jet fuel is the single fuel, and JP-8 is the primary DoD standard fuel. Drop-in synthetic jet fuel blends will be identified as JP-8 once the specification is fully revised. End users will not know whether the JP-8 they have is made from petroleum or from other resources.

A plethora of acronyms and terminology are associated with alternative fuels generally, and this is certainly no different for alternative jet fuels. The terminology is evolving, so what may have been terminology common a couple of years ago to refer to a certain type of alternative jet fuel may no longer be the preferred terminology in use today. In addition, some terms are used interchangeably, although this may or may not be entirely appropriate depending on the context in which they are used. There are a variety of feedstocks and processes by which suitable aviation fuel hydrocarbons might technically be produced, and it remains to be seen how many of these will be commercially viable in the mid-to-far term. This report is only focused on two types of alternative jet fuel, currently designated as blends of JP-8 with Synthetic Paraffinic Kerosene (SPK) produced via the Fischer-Tropsch (FT) process or from Hydroprocessed Esters and Fatty Acids (HEFA), and does not address others that are in various stages of research and development.

Fuel Specifications

The composition of jet fuel is a complex mixture of a large number and variety of hydrocarbon molecules as well as approved additives that may be required. For each batch of finished fuel, the mixture's chemical and physical properties must meet the requirements in the applicable jet fuel specification. These specifications have been evolving to include additional requirements to ensure that novel compositions, i.e., compositions containing hydrocarbons synthesized from nonconventional sources, still result in a mixture acceptable for use as an aviation fuel.

ASTM D1655² is a widely used and referenced commercial jet fuel specification, developed and maintained by ASTM International. Historically, it has limited aviation turbine fuels to those made from conventional sources, i.e., crude oil (petroleum), natural gas liquid condensates, heavy oil, shale oil, and oil sands. It was not until August 2000 that ASTM D1655 first began to address aviation turbine fuels made from non-conventional sources, namely only one semi-synthetic fuel made by a specified manufacturing process. This semi-synthetic fuel was Fischer-Tropsch Isoparaffinic Synthetic Kerosene (FT IPK) made at Sasol's Secunda, South Africa plant in blends of up to 50% by volume with Jet A-1 from Sasol's Natref Refinery in Sasolburg, South Africa). In September 2009, it first began to reference another specification, ASTM D7566, as a means to address a wider variety of processes to manufacture hydrocarbons from non-conventional sources suitable for use as aviation fuel components.

² Numerous commercial fuel specifications and test methods are cited in this report and these are not individually referenced. They are found in the Annual Book of ASTM Standards available from ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA. The vast majority are found in Section 5, Petroleum Products and Lubricants, and the remaining few in Section 14, General Methods and Instrumentation.

ASTM D7566 is a relatively new specification, first issued in September 2009. ASTM D1655 began at that time to reference it, as it provides control for jet fuel containing synthetic components, i.e., hydrocarbons synthesized from nonconventional sources (e.g., coal, natural gas, and biomass). Aviation turbine fuels with synthetic components produced in accordance with ASTM D7566 are deemed to meet the requirements of ASTM D1655, and thus are acceptable for use as an aviation fuel. ASTM D7566 will continue to be revised as novel jet fuel compositions are qualified and certified for aviation use.

As of 1 July 2011, ASTM D7566 defined requirements for both Fischer-Tropsch Synthetic Paraffinic Kerosene (FT SPK) and for Hydroprocessed Esters and Fatty Acids (HEFA) SPK. It also defines requirements for jet fuels containing these synthesized hydrocarbon components or blending stocks. Jet fuel blends containing up to 50% by volume of either FT SPK or HEFA SPK (“50/50” blends) were successfully qualified and certified for use in commercial aviation, and have been allowed for commercial aviation use since September 2009 and July 2011, respectively.

MIL-DTL-83133 is a military specification for military-grade jet fuel, principally JP-8. This specification is also evolving to allow the use of synthesized hydrocarbons. The current Revision H with Amendment 1, released 14 September 2012, includes requirements for both FT SPK and HEFA SPK blending stocks, and also requirements for blends of conventional JP-8 with up to 50% by volume of either FT SPK and with HEFA SPK.

Qualification, Certification and Approval of Alternative Jet Fuels

Alternative jet fuels made from nonconventional feedstocks and via unconventional processes will have compositions that vary from conventional jet fuel. A fuel qualification and approval process is employed to evaluate candidate jet fuels and determine their acceptability for use as an aviation fuel. More details about this process will be discussed in Section III (Approach). In alignment with the Single Fuel on the Battlefield Policy, and implementing Army Regulation 70-12, TARDEC is conducting the RDT&E effort to qualify alternative jet fuels for use as ground fuels in tactical and combat vehicles and equipment.

In the case of aircraft platforms, whether commercial or military, an additional activity known as certification is also pursued. Certification is a Federal Aviation Administration (FAA) term and is a process to validate the air worthiness and safety of flight for a given aircraft. When invoking the certification process, the FAA along with other stakeholders such as DOD, must consider the airframe, the engine(s), and the fuel on which they operate as a system. Changes to any parts of the system requires a new certification process be completed using the new combination of airframe, engine(s), and fuel. However, neither the Army, nor the vehicle OEMs, “certifies” the ground worthiness of a ground vehicle for operation on a specific fuel. Typically, ground engine OEMs recommend certain fuels based on commercial fuel specifications, and often tie warranties for their equipment to the use of these recommended fuels.

DoD and Service Energy Security Initiatives and Goals

There have been a number of strategy and policy documents guiding DoD investments in alternative fuels since 2009. The next several paragraphs will describe only the most recent guidance as of time this report was finalized.

The DoD Operational Energy Strategy, issued for the first time in June 2011, makes it clear that DoD needs to diversify its energy sources as part of a strategy approach to better assure a supply of energy for military missions. (1) Army, Air Force, and Navy efforts to qualify and approve alternative jet fuels for use by the military directly support this strategy. In addition, these efforts will contribute to national goals such as reducing dependence on petroleum, lowering emissions of greenhouse gases, and stimulating innovation in the civilian sector.

The DoD Operational Energy Strategy Implementation Plan, issued in March 2012, documented specific targets and timelines in support of the strategy. (2) One target, to promote the development of alternative fuels, stated a departmental policy and investment portfolio be established for alternative fuels. The DoD Alternative Fuels Policy for Operational Platforms was issued in July 2012, the goals of which are to “ensure operational military readiness, improve battlespace effectiveness”, and increase “the ability to use multiple, reliable fuel sources.” (3)

In June 2013, a memorandum signed by the Deputy Secretary of Defense provided guidance for a comprehensive defense energy policy to be developed during FY14. It states that the defense policy should be consistent with national-level energy guidance, and the Department of Energy should be consulted, as appropriate. (4)

The Army Operational Energy Policy, issued in April 2013, includes policy to increase the use of renewable energy by developing operationally viable alternative energy sources and expanding flexibility in system energy use. (5)

The U.S. Air Force Energy Strategic Plan, issued in March 2013, documents the commitment of the Air Force to diversifying the types of energy sources it will use, such as alternative fuels, and “securing the quantities necessary to perform its missions as a way to *Assure Supply*, both for near-term benefits and long-term energy security.” (6) The Air Force set a goal to certify USAF aircraft to fly on commercially available drop-in fuels by 2016 that are cost competitive with traditional petroleum-based jet fuels, and meet USAF environmental and technical specifications. In addition, the Air Force “intends to increase its use of alternative aviation fuel blends for non-contingency operations to 50% of total consumption by 2025.” By certifying aircraft to fly on different alternative fuel blends, “the Air Force is ensuring it will be ready for whatever private industry is able to bring to the market.”

The Department of the Navy Strategy for Renewable Energy, issued in October 2012, provides guidance relative to Navy energy goals established in 2009, one of which is for Navy to obtain half of its energy from alternative sources by 2020. (7)

III. APPROACH

A roadmap provided in Appendix A shows a high level summary of the evaluations conducted to qualify the SPK/JP-8 blends (FT, HEFA) for use in military ground systems. This roadmap evolved from the technical approach taken, the identified drop-in fuel candidates, and specific evaluations needed to qualify them.

A. Summary of Technical Approach

The approach utilized for qualification was based on a combination of two standard practices: (1) ASTM D4054 “Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives”; and (2) technology maturity evaluations using a modified Technology Readiness Level (TRL) for fuel readiness. While both these are standard practice in the aviation community, including that of the Army, Air Force, and Navy, TARDEC has modified them, as needed, and adopted the revised practices for qualifying alternative fuels for use in DoD ground equipment. Applying these practices, TARDEC is conducting a logical progression of minimal evaluations that ensure the needed knowledge is acquired to effectively qualify candidate alternative fuels for use across the entire span of ground equipment systems employed in military tactical/combat fleets.

Standardized Process (ASTM D4054)

ASTM D4054 is the standard practice used for alternative jet fuel qualification and approval by both commercial and military aviation stakeholders. TARDEC has adopted this approach to qualify and approve alternative jet fuel for use in military ground systems. The standard, shown in Figure 1, outlines a rigorous process by which the fuel is evaluated and, if found acceptable, approved for use. As depicted in Figure 1, there are three phases to this process during which specific tasks are completed.

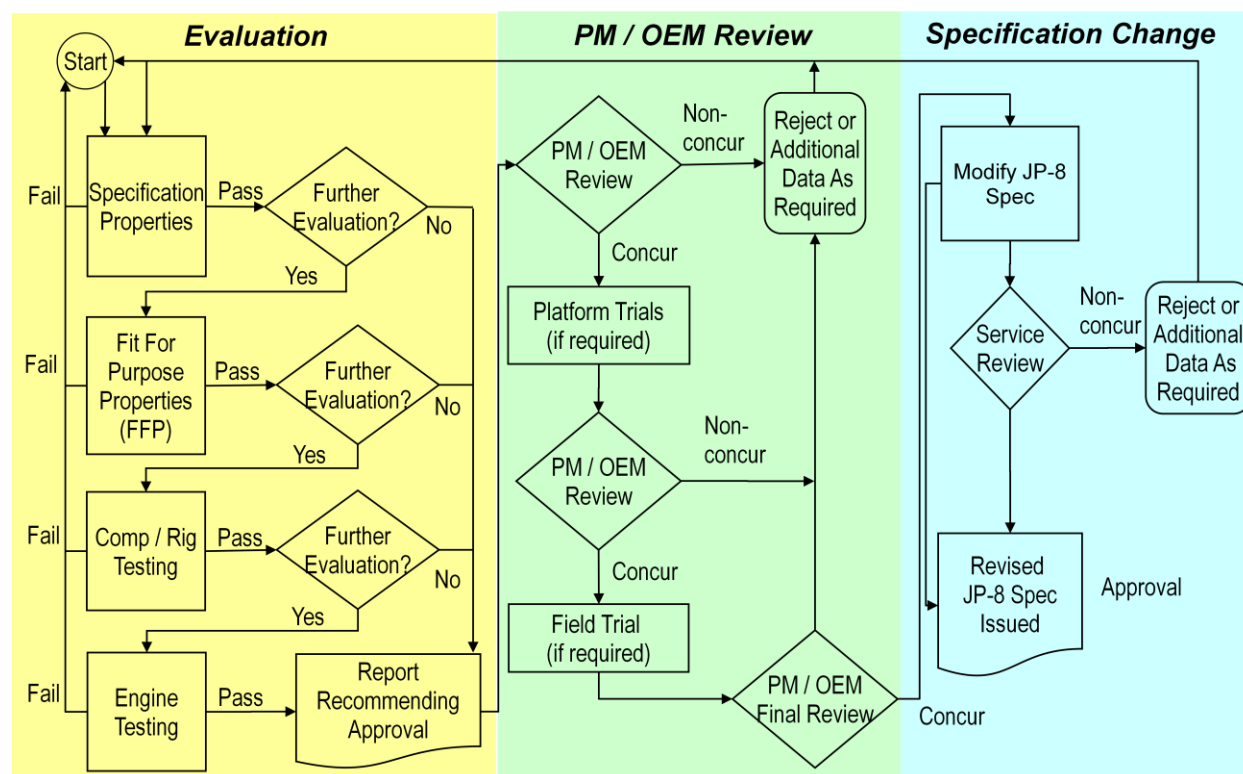


Figure 1 – ASTM D4054, Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives

EVALUATION PHASE

The qualification process begins with an evaluation of the candidate fuel's specification properties. This could be the draft specification properties for the alternative fuel or blend or in the case of a drop-in alternative fuel, the properties of the fuel in the existing specification the alternative fuel is intended to displace. These properties will typically include the basic chemical and physical properties of the fuel.

If all of the candidate fuel's properties are found to pass the requirements called out in the specification, then the next process step is an evaluation of the candidate fuel's "Fit For Purpose" (FFP) properties. Existing fuel specifications were developed over a long period of time and are based on operational experience with petroleum fuels; they do not address all of the properties needed to evaluate or specify non-petroleum based fuels because of the inherent properties of a petroleum-based fuel. These other properties that need to be considered during the evaluation phase are the FFP properties. Materials compatibility, additive compatibility, and additive effectiveness are some examples of FFP properties when evaluating an alternative jet fuel for use in military systems.

If FFP properties are found to be acceptable, then the process continues with component and/or test rig testing. If results from those tests are satisfactory, then engine testing is conducted as the next step in the Evaluation Phase.

The outcome of the Evaluation Phase is a technical Final Qualification Report. The report provides the recommendation that the fuel be approved for Army ground systems use, along with the data and rationale that supports the recommendation.

REVIEW PHASE (PM / OEM)

The Final Qualification Report is submitted for review and/or concurrence by impacted stakeholders (e.g., PMs) who may decide they want to see more data or have validation testing or field service trials conducted. The Review Phase is complete once stakeholders have reviewed and/or concurred with the Final Qualification Report.

SPECIFICATION CHANGE PHASE

The approved fuel is implemented through a change to the existing fuel specification during the Specification Change Phase. It is this change by which the final qualification deliverable, the modified fuel specification, transitions to the Army via the Defense Logistics Agency (DLA). DLA-Energy now has a specification to procure the new alternative fuel for Army ground systems use.

TARDEC is designated in the JP-8 specification as the Army's technical authority for ground fuels and lubricants, and as such TARDEC has provided the Army's position on any modifications made to the JP-8 specification with respect to ground systems. Furthermore, in order to avoid duplication of fuel qualification efforts conducted by various aviation fuel stakeholders including the Air Force, Navy, Federal Aviation Administration, and CAAFI, TARDEC has reviewed and accepted fuel data generated by these entities.

Technology Readiness Levels (TRL)

Assessing the TRL of alternative jet fuels for use in ground systems involves testing and evaluation, conducted in accordance with ASTM D4054. Figure 2 provides a summary of TRL assessment for ground fuels. The Air Force developed a list of tests and/or evaluations for TRL assessment of alternative jet fuels. TARDEC approved this list, with a few modifications as needed for application to ground systems. This list is provided in Appendix A. The most current version of this list as issued by the Air Force can be found in the Department of Defense Handbook, Aerospace Fuels Certification, MIL-HDBK-510. (8)

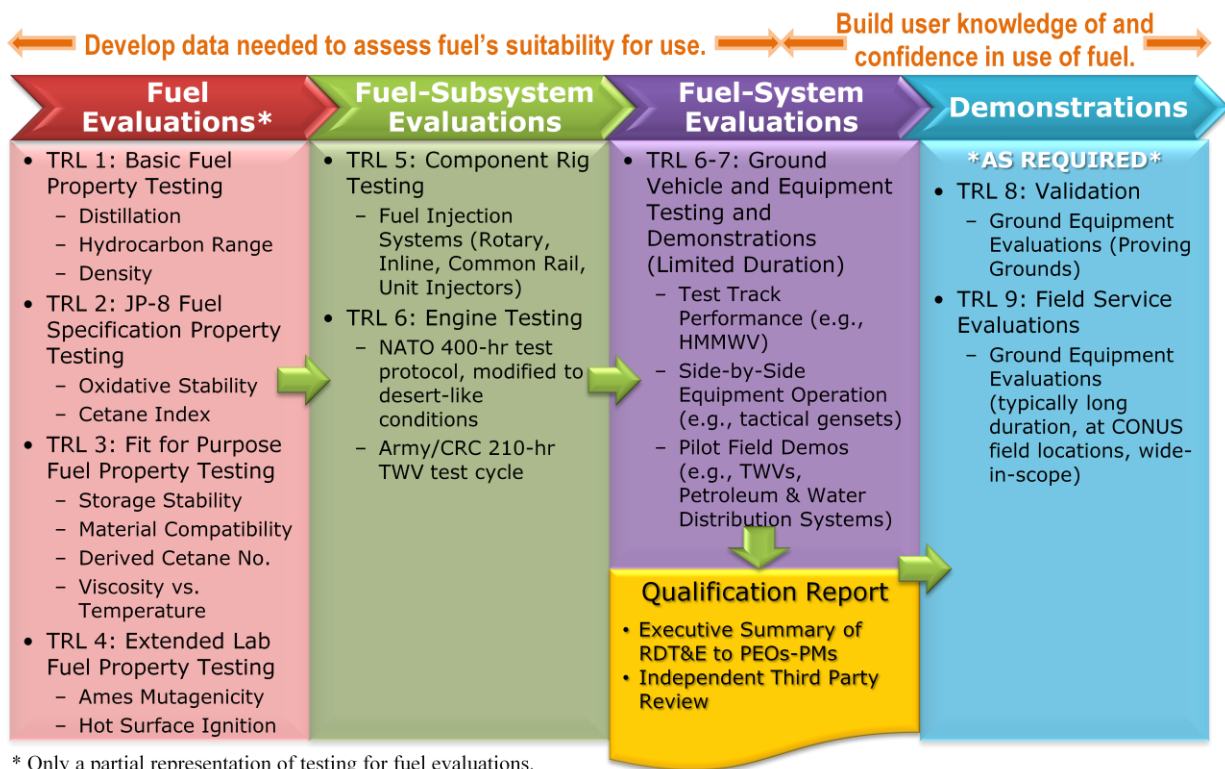


Figure 2 – Technology Readiness Levels for Ground Fuels

B. Identification of JP-8 Drop-in Candidates

The DoD Alternative Fuels Policy for Operational Platforms³ requires the Tri-Service Petroleum, Oils, and Lubricants (POL) Users Group, of which TARDEC FLTT is a long-standing core member, to review the most current report from DOE to identify alternative jet fuel candidates that will likely be commercially competitive with conventional fuels within the next ten years. Even before this policy was established, DOE programs informed DoD scientists and engineers on likely alternative fuel candidates. Certainly this was the case with Fischer-Tropsch fuels as previously explained in this report.

FT SPK Blends

The first candidate alternative jet fuel being qualified as a “drop-in” fuel is a blend of up to 50% by volume of conventional JP-8 and Fischer-Tropsch Synthetic Paraffinic Kerosene (FT SPK). Throughout this report, this blend may be designated as FT SPK blend or SPK blend (FT). FT SPK is manufactured by a three-step process: (1) reforming natural gas or gasifying coal, biomass, or other carbonaceous resources into synthesis gas, (2) converting that synthesis gas into primarily long-chain paraffinic hydrocarbons via the Fischer-Tropsch (FT) catalytic reaction, and (3)

³ The Department of Defense Alternative Fuels Policy for Operational Platforms is pursuant to 10 U.S.C. § 138c.

rearranging those long-chain hydrocarbons into molecules that fall within the aviation-grade kerosene (jet) boiling range by employing catalytic hydroprocessing reactions already used in petroleum (crude oil) refining. The hydroprocessing step typically employed combines hydrocracking and isomerization reactions.

HEFA SPK Blends

The second candidate alternative fuel being qualified as a “drop-in” fuel is a blend of up to 50% by volume of conventional JP-8 and SPK consisting of Hydroprocessed Esters and Fatty Acids (HEFA SPK). Throughout this report, this blend may be designated as HEFA SPK blend or SPK blend (HEFA). HEFA SPK is manufactured by employing hydroprocessing reactions that convert plant, algae, and animal oil or fat based fatty acids, and/or the esters derived from them, into suitable hydrocarbons. An initial processing step first removes unwanted oxygen from the fatty acids and esters to produce long-chain normal paraffins, and then a hydrocracking / isomerization processing step is done to convert these long-chain paraffins into hydrocarbons in the kerosene boiling range suitable for use as an aviation-grade jet fuel blending stock.

One other note about HEFA SPK is that initially it was known as Hydroprocessed Renewable Jet or HRJ. Many of the reports issued on evaluations of HEFA SPK utilize the HRJ nomenclature.

Concurrent Qualification of FT SPK and HEFA SPK Blends

FT SPK/JP-8 blended fuel was the first candidate the Alternative Fuels Qualification Program at TARDEC began evaluating as a JP-8 drop-in fuel. When HEFA SPK/JP-8 blended fuel entered the TARDEC qualification effort, results from TRL 1-4 evaluations completed established the fact that the chemical composition and physical properties of HEFA SPK are very similar to those of FT SPK. (9) (10) Based on these results, TARDEC began a concurrent qualification of both SPK blends (FT and HEFA). Concurrent qualification is defined for the purpose of this report as some TRL 5-7 tests were conducted with FT SPK blends, while other tests were conducted with HEFA SPK blends. The results from tests with either fuel are considered sufficiently representative of the other fuel.

“50/50” Blends and Maximum Allowable Blending Ratio

A key aspect worth mentioning to avoid any misunderstanding of alternative fuel blends is the fact that the JP-8 specification calls out property requirements for the SPK blends (FT, HEFA) that in many cases will limit the maximum blending ratio to something less than “50/50” (synthetic-to-petroleum ratio). Typically, either the minimum allowable density or minimum allowable aromatic content are the limiting factors. (11) SPK blends purposely created at “50/50” maximum blending ratio, while still meeting the other required properties to the greatest extent possible, were used throughout all qualification testing to establish impacts to equipment performance and durability from operation with the most extreme (“worst case”) candidates for JP-8 drop-in fuels.

C. Identification of Evaluations Conducted

Fuel Evaluations

TRL 1-4 evaluations focus on testing the candidate fuel properties and are summarized as follows:

- TRL 1 – Basic Fuel Properties (e.g., distillation, hydrocarbon range, density, etc.)
- TRL 2 – Fuel Specification Properties (e.g., oxidative stability, cetane index, etc.)
- TRL 3 – Fit-for-Purpose Properties (e.g., storage stability, material compatibility, etc.)
- TRL 4 – Extended Lab Fuel Properties (e.g., Ames mutagenicity, hot surface ignition, etc.)

TRL 1-4 evaluations are the key to understanding the composition, properties, compatibility, environmental, and basic health-related aspects of the neat⁴ alternative fuels (or fuel blending stocks), and any proposed fuel blends. A list of all the properties selected for the TRL 1-4 fuel evaluations can be found in Appendix A.

Basic property tests selected for the TRL 1 fuel evaluation are intended to reveal as much information to initially characterize the fuel as possible without requiring a significant volume of the fuel. Additional property tests selected for the TRL 2 fuel evaluation generate data for the remainder of chemical and physical properties listed in the main property requirements table for the targeted existing (petroleum) fuel specification that the candidate drop-in fuel will replace. The property tests selected for the TRL 3 fuel evaluation go beyond what is in the existing targeted fuel specification to generate information with the intent to determine whether or not the fuel is fit for the intended purpose (the FFP, or “Fit-for-Purpose” Properties). In terms of evaluating aviation grade kerosene for potential use in compression ignition (diesel) engines, TARDEC selected two additional FFPs – cetane number (derived) and high temperature kinematic viscosity (at 40°C). Finally, extended laboratory fuel properties selected for the TRL 4 evaluation generate data about either the environmental, safety, and occupational health characteristics of the fuel, or about system-specific characteristics that still can be performed in the laboratory with small volumes of fuel rather than in a test cell and, therefore, requiring larger volumes of fuel.

MIL-HDBK-510, Aerospace Fuels Certification, provides a comprehensive guide for evaluation and certification of aviation fuels. (8) This handbook is a significant source for information on jet fuel evaluations, and includes a number of figures providing data on properties of typical petroleum jet fuels (JP-8, Jet A-1, Jet A, etc.). This data is particularly useful in fuel evaluations for analysis of how the properties of candidate drop-in jet fuels compare with those of current petroleum jet fuels.

Fuel-Subsystem Evaluations

TRL 5-6 evaluations focus on testing subsystems operated with the candidate fuel and they are summarized as follows:

- TRL 5 – Fuel Injection Systems
- TRL 6 – Engines

TRL 5-6 evaluations study the impacts use of candidate alternative fuels will have on the performance and durability of subsystems. The approach these evaluations typically use is to

⁴ Neat fuels are defined as “fuel that is free from admixture or dilution with other fuels.” (DOE Alternative Fuels Glossary of Terms)

compare test results from operating the subsystems on JP-8 (baseline testing) and on the candidate fuel to assess the drop-in capability of the candidate fuel.

These key factors were taken into account to identify the specific fuel injection systems and engines to test in TRL 5-6 evaluations:

- density of the subsystems in the current fleet
- representation from amongst the main categories of ground systems (tactical vehicles, combat vehicles, tactical generator sets, and ground support equipment)
- representative technologies (fuel injection systems and engines) spanning across the current fleet, as well as likely near-term additions to the fleet
- equipment most at risk (e.g., more sensitive to certain fuel properties such as lubricity, cetane number, compressibility, etc.)

FUEL INJECTION SYSTEMS

For ground systems, TRL 5 evaluations focus on engine fuel injection system (FIS) performance and durability while operating on the candidate alternative fuel. FIS are commercial-off-the-shelf components that are designed and calibrated to operate with diesel fuel. Some FIS are more sensitive to fuel properties such as lubricity, density, and viscosity, causing their performance and/or durability to be at higher risk. These FIS rely on several fuel properties to perform as designed; they rely on density and viscosity to prevent mistimed injections, and on lubricity to prevent premature wear. The variation in these key properties between diesel fuel and jet fuel (JP-8, JP-8 drop-ins), as allowed by the associated fuel specifications, is the reason these sensitive FIS are considered higher risk when operating on JP-8 fuel or candidate JP-8 drop-in fuels.

Two types of FIS were identified to be at highest risk and selected for evaluation. These FIS were evaluated with a number of fuels and different operating conditions and temperature:

- Rotary distributor fuel injection pump (Stanadyne) – High density in current military systems
- High Pressure Common Rail (HPCR) – Future military systems

ENGINES

TRL 6 evaluations consisted of dynamometer testing of several engines. The following is the list of the eight engines selected:

- General Engine Products (GEP) 6.5L Turbo
- Caterpillar (CAT) C7
- Detroit Diesel Corporation (DDC)/MTU 8V92TA
- Cummins VTA-903T
- Navistar MaxxForce 9.3D
- Ford 6.7L “Scorpion” Powerstroke
- Continental AVDS 1790-8CR*
- Honeywell (Lycoming) AGT1500*

Dynamometer testing of the last two engines in this list (marked with an asterisk), the Continental AVDS 1790-8CR and the Honeywell AGT1500 engine, was not completed, although for two different reasons as summarized here:

Continental AVDS 1790-8CR: Testing of this engine was initiated at the TARDEC Ground Vehicle Power and Mobility (GVPM) laboratory. However, this testing was aborted when it became clear that the integrity of the two rebuilt engines procured for this project was deficient.

Honeywell (Lycoming) AGT1500: This engine is a gas turbine engine that is used to power the M1 Abrams main battle tank. TARDEC determined that testing of this engine is not needed to qualify candidates as drop-in fuels for JP-8 for a few reasons. First, aviation-grade kerosene fuels, such as SPK/JP-8 blends or even current JP-8, are known to be very well-suited for use in gas turbine engines, including the recuperative-type AGT-1500 turbine engine. Second, generally gas turbine engines are multi-fuel capable. Third, significant testing of gas turbine (aviation) engines operating on the SPK/JP-8 blends has already been conducted by commercial and military stakeholders with positive results.

The other six engines in the down-selected list were tested with either a 50% (by volume) blend of FT SPK/JP-8 and/or HEFA SPK/JP-8. Based upon the compositional similarities of FT SPK and HEFA SPK as previously discussed, TARDEC decided that testing with either SPK blend (FT or HEFA) would provide sufficient data and understanding of the impacts on engines when operating on either blend.

The various engine models and technologies amongst those which were selected for dynamometer testing are diverse. Collectively, these engine technologies are representative of those found in a majority of the Army/DoD tactical and combat ground vehicle fleets as shown in Table 1. The exception to this latter point is the Ford 6.7L Powerstroke engine. This modern engine, with a high pressure common rail fuel injection system, is of potential interest for use in tactical vehicles and is already found in some ground support equipment in use by the Air Force.

Table 1 – Dynamometer Tested Engines Representative of Army/DoD Ground Vehicle Fleet

Engine	Displacement / Cylinders	Rated Peak Power / Torque	Combustion Process	Fuel Injection System	Some Examples of Vehicles With This or Similar Engine
GEP	6.5 L / V8	190 hp @ 3400 rpm / 380 ft·lb _f @ 1800 rpm	Indirect Injection	Rotary Pump-Line-Nozzle Injectors	HMMWV
CAT C7	7.24 L / I-6	330 hp @ 2200 rpm / 860 ft·lb _f @ 1440 rpm	Direct Injection	Hydraulic Electronic Unit Injectors (HEUI)	Stryker Family of Vehicles Family of Medium Tactical Vehicles HEMTT (Heavy Expanded Mobility Tactical Truck) – A4 HETS (Heavy Equipment Transporter System) – M1070A1 PLS (Palletized Load System) – A1
DDC 8V92TA	12.0 L / V8	445 hp @ 2150 rpm / 1250 ft·lb _f @ 1200 rpm	Direct Injection	Mechanical Unit Injectors	HEMTT PLS – M1074, M1075 HETS – M1070, M1975, M1977
Cummins VTA-903T	14.8 L / V8	600 hp @ 2600 rpm / 1025 ft·lb _f @ 2350 rpm	Direct Injection	Mechanical Unit Injectors	Bradley Fighting Vehicles
Navistar MaxxForce 9.3D	9.3 L / I-6	375 hp @ 2000 rpm / 1250 ft·lb _f @ 1200 rpm	Direct Injection	Electro-Hydraulic Unit Injectors	MRAP (Mine Resistant Ambush Protected) Vehicle
Ford Powerstroke ¹	6.7 L / V8	320 hp @ 2800 rpm / 700 ft·lb _f @ 1800 rpm	Direct Injection-Electronically Controlled	High Pressure Common Rail with Piezo Electric Injectors	Engine technology of potential interest for future military ground vehicles

Table Footnotes:

1. Export version of this engine.

Fuel-System Evaluations

TRL 6-7 evaluations focus on testing and demonstrating systems operated with the candidate fuel and are summarized as follows:

- TRL 6 – System Tests
- TRL 7 – System Demonstrations

TRL 6-7 evaluations study the impacts that the use of candidate JP-8 drop-in fuels will have on the operability, performance, and/or durability of systems. These evaluations may include comparison of results from systems operated on JP-8 (baseline testing) and on the candidate fuel as the basis to assess the drop-in capability of the candidate fuel.

Identifying the specific systems to test or demonstrate in TRL 6-7 evaluations took into account these key factors:

- density of the systems in the current fleet
- representation from amongst the main categories of ground systems (tactical vehicles, combat vehicles, tactical generator sets, and ground support equipment)
- representative technologies spanning across the current fleet, and also likely near-term additions to the fleet

TACTICAL GENERATOR SETS

A number of different sizes of DoD tactical generator sets were incorporated into TRL 6-7 evaluations. The generator sets included the following:

- MEP 531A (2-kW)
- MEP 831A (3-kW)
- MEP 802A (5-kW)
- MEP 803A (10-kW)
- MEP 804A and 804B (15-kW)
- MEP 805B (30-kW)
- MEP 807A (100-kW)

The selection of these generators, with the exception of the 5-kW, was accomplished through coordination with the Communications-Electronics Center of the Research, Development, and Engineering Command (CERDEC). CERDEC includes the Power Division of the Command, Power & Integration Directorate that provides engineering support for tactical generator sets.

TACTICAL GROUND VEHICLES

A number of different vehicles were operated on the candidate alternative fuel blends during TRL 6-7 evaluations. The vehicles included the following:

- HMMWV (High Mobility Multipurpose Wheeled Vehicle), including one up-armored variant
- M925 Cargo Truck
- M939 Truck Series
- M915 Line Haul Truck Tractor
- LMTV (Light Medium Tactical Vehicles)
- MTV (Medium Tactical Vehicles)
- FMTV (Family of Medium Tactical Vehicles)
- HEMTT (Heavy Expanded Mobility Tactical Truck)
- PLS (Palletized Load System)

GROUND SUPPORT EQUIPMENT

A number of different types of equipment were incorporated into TRL 6-7 evaluations. This equipment included the following:

- Crane 7.5T
- Forklift 10K
- Containerized Kitchen (CK)
- Laundry Advanced System (LADS)
- Tank and Pumping Unit (TPU)
- Advanced Aviation Forward Area Refueling System (AAFARS)
- Fuel System Supply Point (FSSP)
- Petroleum and Water (PAWS) storage, distribution, and handling equipment including pumps, hoses, valves, adapters, and collapsible storage bladders

The evaluations of petroleum and water distribution equipment focused on Army-unique systems. The Air Force and Navy completed a number of other evaluations involving fuel storage, distribution, and handling equipment.

D. Protocols for Evaluations

Fuels

A wide variety of protocols, nearly all standardized test methods, were employed for fuel evaluations. These protocols are referenced in the reports and papers on fuel evaluations for SPK (FT and HEFA) and the blends of SPK with JP-8 (or near equivalents JP-5, Jet A-1 and Jet A), of which only a small fraction are cited herein. (11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33)

BASIC AND SPECIFICATION PROPERTIES

Basic and specification properties of the fuel were determined using standardized test methods, typically in accordance with methods developed as ASTM petroleum standards. A list of the test methods employed is provided in Appendix A, TRL 1 and TRL 2 tests.

FIT-FOR-PURPOSE PROPERTIES

As explained in Section IIIA (Summary of Technical Approach), existing fuel specifications do not address all of the properties needed to evaluate or specify non-petroleum based fuels. These other properties are known as Fit-For-Purpose (FFP) properties. A list of the test methods employed to determine FFP properties can be found in Appendix A, TRL 3 tests; most of these are standardized test methods such as ASTM methods. Note that two properties, cetane number and kinematic viscosity at 40°C, are of relevance in assessing the suitability of fuel for use in ground (compression ignition) engines. The majority of the FFP testing was conducted by the Air Force, the Navy (JP-5 drop-in candidates), and the broader aviation community engaged in collaborative efforts to qualify and approve alternative aviation fuels for use in commercial and military aviation platforms.

EXTENDED LABORATORY FUEL PROPERTY TESTING

A list of the test methods employed for extended laboratory fuel property testing is provided in Appendix A, TRL 4 tests. Note that cetane number is on this list. This test is different from the test for derived cetane number completed during TRL 3. Cetane number testing requires more extensive laboratory set-up and fuel volumes, and generates data comparable to extensive data that exists for diesel fuel. As shown in Appendix A, both cetane number and derived cetane number tests are ASTM standardized methods.

Fuel Injection Systems

Fuel pump stand rigs, designed and built by the Army lab located at Southwest Research Institute were employed for evaluating fuel injection system performance and durability when operating on the SPK blends. The testing protocols used were based on standardized methods published by either ASTM International or the North Atlantic Treaty Organization (NATO). (17, 34, 35, 36, 37)

ROTARY DISTRIBUTOR FUEL INJECTION PUMP (STANADYNE)

The evaluation for this pump utilized a configured fuel pump stand rig developed to control temperature and operation of the pumps in accordance with ASTM D6898 “Evaluating Diesel Fuel Lubricity by an Injection Pump Test Rig”. The pumps were inspected before and after each test for noticeable wear and fuel lubricity effects in accordance with manufacturer specifications. Test fuels were tested at the beginning and conclusion of each test using bench-top lubricity methods according to ASTM D6079 – High Frequency Reciprocating Rig (HFRR), ASTM D5001 – Ball-on-Cylinder Lubricity Evaluator (BOCLE), and ASTM D6078 – Scuffing Load BOCLE (SLBOCLE) to determine any fuel lubricity degradation.

Table 2 provides a summary of the test parameters, while Tables 3 provided the details for the test matrix.

Table 2 – Summary of Pump Test Rig Test Parameters

Test Parameters	Test Condition
Targeted Testing Duration, hours	1000
Operating Fuel Temperature, °F	105, 135 and 170
Pump Speed, rpm	1700

Table 3 – Elevated Temperature Rotary Distributor Fuel Injection Pump Test Matrix

Test No.	Test Fuel	Operating Fuel Temperature		
		105°F	135°F	170°F
1, 2, 3	No. 2DS15 (as purchased)	X	X	X
4	No. 2DS15, Clay Treated	X		
5	Jet A-1, no CI/LI	X		
6, 8, 10	Jet A-1 with QPL additive 1 (DCI-4A) at 22.5 g/m ³	X	X	X
7, 9, 11	Jet A-1 with QPL additive 2 (NALCO 5403) at 22.5 g/m ³	X	X	X
12, 13, 14	Jet A-1 with commercial additive at max. rate	X	X	X
15	SPK (FT), no CI/LI	X		
16, 17, 18	Test No. 15 Fuel with best additive* at max rate	X	X	X
19, 20, 21	Jet A-1 / SPK (50/50 blend) with best additive* at min rate	X	X	X

*Best additive per results from Tests No. 6-11 (DCI-4A)

HIGH PRESSURE COMMON RAIL (HPCR)

High pressure common rail (HPCR) fuel injection systems are being found more commonly on modern CI engines including some candidate newer repower engines for the Army's ground equipment fleet. As the name implies, HPCR systems operate at higher injection pressures (~ 2,200 bars or 32,000 psi) than most of the Army's traditional fuel injection systems, and provide better control for various operating modes such as fuel economy, power, and low emissions. HPCR systems, though, are inherently more sensitive to some fuel characteristics such as lubricity and viscosity, especially with operation at elevated temperatures.

TARDEC identified three HPCR systems for evaluation: Cummins ISL engine XPI system; Ford 6.7L Powerstroke engine system designed by Bosch; and a John Deere 4.5L system. Each HPCR system was evaluated using a customized FIS test rig that controlled fuel temperature and allowed for each HPCR system to be controlled by its OEM-provided engine control module (ECM). (35, 36, 37) The testing employed an operating cycle based on a modified NATO 400 hour engine endurance cycle. The test fuels were each tested for lubricity degradation at the 0 hr and 100 hr increments of the 400 hour test. Wear analyses of the HPCR systems were conducted at the start and conclusion of each test per manufacturer's recommendations. Table 4 provides the complete test matrix for the HPCR evaluation.

Table 4 – HPCR Evaluation Test Matrix

Fuels^{1, 2}	Test Temperature	High Pressure Common Rail System		
		Cummins XPI	Ford 6.7L Powerstroke	John Deere 4.5L
ULSD	Standard – 60°C	X	X	X
Jet A - no CI/LI		X	X	
Jet A - min CI/LI ³		X	X	X
FT SPK - no CI/LI		X	X	
FT SPK - min CI/LI			X	X
FT SPK - max CI/LI		X		
50/50 Blend of Jet A / FT SPK - min CI/LI			X	X
50/50 Blend of Jet A / FT SPK - max CI/LI ³		X	X	
FT SPK - min CI/LI	Elevated – ~80°C		X	
Jet A - min CI/LI			X	
50/50 Blend of Jet A / FT SPK - max CI/LI				X
Jet A - min CI/LI ³	Elevated – >90°C	X		X
FT SPK - min CI/LI				X
FT SPK - max CI/LI				
50/50 Blend of Jet A / FT SPK - min CI/LI				X
50/50 Blend of Jet A / FT SPK - max CI/LI ³		X		X

Table Footnotes:

1. JP-8 used in Cummins tests, but otherwise in all other testing Jet A used as representative of JP-8.
2. As indicated, some fuels were additized with Corrosion Inhibitor/Lubricity Improver (CI/LI) per QPL-25017.
3. JP-8 with “as received” treat rate of CI/LI was used in Cummins XPI tests.

Engines

Engine dynamometer testing was conducted to better understand and determine fuel effects on engine performance and durability. Two different types of evaluations were completed. One type of evaluation focused specifically on better understanding of fuel property effects on engine performance. (38) The other type of evaluation focused on determining both engine performance and durability with operation on the candidate drop-in fuels. (39, 40, 41, 42, 43, 44, 45, 46, 47)

CETANE WINDOW

Engine cetane window evaluations were conducted to better understand the impacts that various fuel properties have on the performance of selected engines used in military ground vehicles. Specifically the two engines selected for this study were the GEP 6.5L turbocharged V-8 engine and

the Caterpillar (CAT) C7 inline 6-cylinder engine. The GEP engine was selected because of its high density in the fleet and its known sensitivity to several key fuel properties. The CAT engine was selected because it is a more modern engine design, for instance employing electronically-controlled unit injectors, and thus is more representative of newer engines in the fleet. The key study objective was to identify the range for fuel cetane number (“cetane window”) that would provide for trouble-free engine performance. As other fuel properties such as density, energy density, and bulk modulus also impact engine performance, these were evaluated during the study so that cetane number results could be normalized based on variations in these properties.

PERFORMANCE AND DURABILITY

Engine performance and durability evaluations were conducted using either a modified NATO Standard Diesel & Spark Ignition Engines Laboratory Test⁵ with a 400 hour engine endurance cycle, or a 210 hour U.S. Army Tactical Wheeled Vehicle (TWV) engine endurance cycle, or both (limited).

In most cases, two new engines were operated per test protocol, one as a baseline with JP-8, the other for comparison with the alternative fuel blend. When only one engine was operated, it was rebuilt after the first test, which was typically the baseline test. Engine and fuel system wear analyses were conducted to evaluate and quantify any wear differences between the baseline engine and the alternative fuels engine tests. Table 6 provides a summary of the engine test matrix.

⁵ Allied Engineering Publication, AEP-5, Edition 3, May 1988

Table 5 – Engine Test Matrix

Engine	Test Fuel¹	Test Protocol	Operating Temperature
GEP 6.5LT	FT SPK / JP-8 Blend	400-hr NATO (modified)	Ambient ²
	HEFA SPK / JP-8 Blend	400-hr NATO (modified)	Ambient
Caterpillar C7	FT SPK / JP-8 Blend	400-hr NATO (modified)	"Desert-like" ³
	FT SPK	210-hr Army TWV Cycle (2×)	"Desert-like"
DDC 8V92TA	FT SPK / JP-8 Blend	400-hr NATO (modified)	Ambient
Cummins VTA-903T	FT SPK / JP-8 Blend	400-hr NATO (modified)	"Desert-like"
Navistar MaxxForce 9.3D	HEFA SPK / JP-8 Blend	400-hr NATO (modified)	"Desert-like"
Ford 6.7L Powerstroke	FT SPK / JP-8 Blend	210-hr Army TWV Cycle ⁴	Elevated ⁵
	FT SPK	210-hr Army TWV Cycle ⁴	Elevated

Table Footnotes:

1. Although not shown in this table, all test protocols for all engines tested included a JP-8 baseline test.
2. Ambient conditions are 77°F inlet air and 86°F supply fuel per NATO AEP-5.
3. "Desert-like" conditions are 120°F inlet air and a realistic operational supply fuel temperature (supplied by TARDEC GVPM expert) for the NATO AEP-5 cycle; for the 210-hr TWV Cycle, the coolant, oil, fuel and inlet air temperatures are elevated to maintain oil sump temperature of 260°F.
4. The 210-hr Army TWV Cycle was slightly modified by reducing the engine soak time from 10 hrs to 3 hrs, increasing the cycle at rated speed/load from 2 hr to 2 hr 10 min, and employing an additional 2 hr rated speed/pad step to yield a daily operational cycle of 21 hrs that maintained the proportion of total rated to idle hours consistent with the standard 210-hr cycle.
5. For the Ford 6.7L, specifications adopted from Ford for testing maintained the primary engine coolant temperature at 203±3°F and the secondary auxiliary coolant loop at 100±3°F over the test duration; this resulted in a fuel inlet temperature of ~85-90°F average, well below temperatures that have been experienced for military vehicles operating in desert conditions.

Modified NATO AEP-5 (400 Hour): The 400 hour NATO test cycle described in AEP-5 is composed of a performance test and an endurance test. The endurance test is an accelerated durability test to simulate extended conditions over which a combat vehicle engine is expected to be durable and to maintain performance. During the endurance test, a high average load, load cycling, and over-speed conditions are performed to stress the engine.⁶ Table 7 summarizes the endurance test ten hour cycle.

⁶ As provided by P. Sons, Continental AVDS 1790-8CR Test Plan

Table 6 – NATO AEP-5 Endurance Test Ten Hour Cycle

Sub-cycle	Speed	Load ⁵	Duration (hrs)
1	Idle ¹	0% ⁶	0.5
2	100%	100%	2
3	Governed Speed ²	Engine Output	0.5
4	75%	100%	1
5	Idle ¹ --- 100% ³	0% (4 min) --- 100% (6 min)	2
6	60%	100%	0.5
7	Idle ¹	0% ⁶	0.5
8	Governed Speed ⁴	70%	0.5
9	Maximum Torque Speed	100%	2
10	60%	50%	0.5

Table Footnotes:

1. Deviations in fuel temperature are permitted in this sub-cycle.
2. The engine speed shall be obtained with the engine at full throttle and with minimum load.
3. The control movement from IDLE to 100% rated speed/load shall occur within 3 seconds.
4. The engine speed shall be the steady speed of the engine at full throttle and 70% of the rated load.
5. Part loads shall be determined based on the initial performance test.
6. A small load may be applied to reduce vibration damage to the test prop-shaft.

The performance cycle (horsepower and torque) of each engine was tested utilizing an incremental speed test conducted periodically at: wide-open throttle, 100 hour increments during the endurance testing starting at zero hour, and the specified operating conditions. These tests were performed to evaluate and compare the effects of the endurance tests, and in this case the different fuel on the engine's horsepower and torque throughout the test duration. Tables 7 and 8 provide summaries of an example performance cycle and performance matrix.

Table 7 – Example Performance Cycle

Speed (rpm)	Throttle (%)	Time (min)
Idle	0	15
1200	100	10
1440	100	10
1600	100	10
1800	100	10
1925	100	10
2200	100	10
2400	100	10

Table 8 – Example Performance Matrix

Endurance Hours	Fuels and Engines		Temperature
	JP-8	SPK Blend*	
	Engine	Engine	
0	1 and 2	1 and 2	Std., Elev.
100	1	2	Std., Elev.
200	1	2	Std., Elev.
300	1	2	Std., Elev.
400	1 and 2	1 and 2	Std., Elev.

* SPK blend is 50/50 by volume FT SPK and JP-8.

U.S. Army Tactical Wheeled Vehicle Cycle (210 Hour): The U.S. Army 210 hour Tactical Wheeled Vehicle (TWV) engine endurance cycle was developed specifically for predicting fuel/lubricant compatibility with tactical wheeled vehicle engines.⁷ The cycle includes 15 days of operation, each comprising five two-hour periods of rated power operation, alternated with four one-hour periods of idle operation, for a total of 14 hours per test day. The remaining 10 hours of each test day are engine-off “soak” time, during which the engine system cools to ambient conditions; the soak time does not contribute to the 210-hour operational total. Test time is accumulated only during the running segment. The test continues for 210 hours or until the oil degrades to the point of oil condemnation limits, whichever occurs first. (42) Table 9 summarizes a single day of the TWV cycle that is repeated 15 times for the full 210 hour test.

Table 9 – TWV Daily Cycle

Duration (hrs)	Load (%)	Speed (rpm)	Water Temperature ^{1,2} (°F)
2	100	Rated, ± 25	180 ± 5
1	0	Idle	100 $\pm 5^3$
2	100	Rated, ± 25	180 ± 5
1	0	Idle	100 $\pm 5^3$
2	100	Rated, ± 25	180 ± 5
1	0	Idle	100 $\pm 5^3$
2	100	Rated, ± 25	180 ± 5
1	0	Idle	100 $\pm 5^3$
2	100	Rated, ± 25	180 ± 5
10	Engine-off “soak” time		

Table Footnotes:

1. Fuel supply temperature controlled to 90°F $\pm 5^\circ$ F.
2. Oil temperature indirectly controlled by not allowing coolant temperature to exceed 240°F.
3. This temperature attained within 10 minutes of starting idle.

Similar to the NATO AEP-5 cycle, a performance test cycle was conducted with each engine, but for this cycle only prior to and at the completion of the endurance TWV cycle. During the performance test, the engines were set to run at full power at ten engine speeds including the peak torque, rated, and governed speeds.

In the testing of the Ford Powerstroke engine only, the standard TWV daily cycle was modified from what is shown in Table 9. The engine soak time was reduced from 10 hrs to 3 hrs which allowed accelerated testing with 6 cycles daily of 2 hr 10 min duration at rated speed/load. An additional 2 hr cycle at rated speed/load was added at the end of the last 1 hr at idle, and then engine shutdown and 3 hr soak time after that to end the daily 21 hr operational cycle. (47)

⁷ Coordinating Research Council, Inc., “Development of Military Fuel/Lubricant/Engine Compatibility Test,” CRC Report No. 406, January 1967.

Tactical Generator Sets

Three types of evaluations were conducted for tactical generator sets when operating on the SPK blends. The first evaluation assessed performance by operating tactical generator sets side-by-side on various fuels. (48) The other two evaluations focused on determining performance and durability with operation on SPK blends. (49)

SIDE-BY-SIDE OPERATION

The evaluation of tactical generator sets during side-by-side operation was conducted in coordination with CERDEC and PM-Mobile Electric Power (PM-MEP). This demonstration operated three Tactical Quiet Generators, 10-kW, MEP-803A, on three fuels: ULSD, JP-8, and a volumetric blend (50%:50%) of JP-8 and FT SPK. (48) Data captured included engine speed, electrical output, exhaust temperature, inlet fuel temperature, fuel consumption, and exhaust emissions. All three generators had a 25 hour break-in period using ULSD. Two of the generators continued using ULSD to start the 1,000 hour duration test. After 100 hours their operation was alternated between operation with JP-8 and FT SPK/JP-8 blend at 450 hour intervals for the remainder of the test. The third generator was operated on FT SPK for the entire 1,000 hour test. The generators operated at 50% capacity throughout the total 1,000 hour test duration. Table 10 provides a summary of the test matrix for this demonstration.

Table 10 – Tactical Generator Set Side-by-Side Operation Test Matrix

Generator Set 1		Generator Set 2		Generator Set 3	
Run Time	Fuel	Run Time	Fuel	Run Time	Fuel
25 hrs break-in	ULSD ¹	25 hrs break-in	ULSD	25 hrs break-in	ULSD
100 hrs	ULSD	1000 hrs	FT SPK	100 hrs	ULSD
450 hrs	JP-8			450 hrs	JP-8
450 hrs	FT SPK blend ²			450 hrs	FT SPK blend

Table Footnotes:

1. ULSD is 2007 Certification Diesel.
2. SPK Blend is 50/50 by volume FT SPK or HEFA SPK and JP-8.

PERFORMANCE AND DURABILITY

The tactical generator set performance and durability evaluations were conducted in coordination with CERDEC and PM-Mobile Electric Power (PM-MEP) in order to obtain concurrence for approval of the alternative fuel blends. The evaluations were performed in accordance with MIL-STD-705C, specifically the portions focused on reliability and performance. (49, 50) As with the tactical ground engines, a down-select of representative tactical generator sets were evaluated utilizing the alternative fuel blends. Table 11 provides a summary of the generator sets selected for evaluation.

Table 11 – Tactical Generator Sets Matrix

Model	Output	Engine Model #	Engine Manufacturer
MEP 531A	2-kW	L48AE-DEG	Yanmar
MEP 831A	3-kW	L70AE-DEGFR	Yanmar
MEP 803A	10-kW	DN4M-1	Onan/Lister Petter
MEP 804A	15-kW	C-240PW-28	Isuzu
MEP 804B	15-kW	4TNV84T-DFM	Yanmar
MEP 805B	30-kW	4039T	John Deere
MEP 807A	100-kW	3126B	Caterpillar

Performance Test: The performance portion of the evaluation was conducted in accordance with MIL-STD-705C. Electrical characteristics were evaluated using methods TM 608.1, TM 608.2, and TM 630.1, at one voltage connection level. Testing at elevated altitude and temperature was completed at two conditions (4,000 ft and 95°C, and 10,000 ft and 95°C) using method TM 720.1. Environmental tests were conducted at 125°F using method TM 710.1 (specifically 710.1.3.2.g) and at -50°F using method TM 701.1 (specifically 701.1.3.2.k). Finally, fuel consumption was evaluated using method TM 670.1.

Reliability Test: The reliability portion of the evaluation was conducted in accordance with MIL-STD-705C TM 695.1 and with a target total runtime of 1500 hours per generator set. The 1500 hours was completed using the cyclic load schedule shown in Table 12.

Table 12 – Generator Set Reliability Cycle (Ref. MIL-STD-705C; Method 695.1a)

Run Number	Rated Load (%)	Run Duration (hrs)
1	50	24
2	0 (Idle)	4
3	75	24
4	25	24
5	100	24

Tactical Ground Vehicles and Ground Support Equipment

Three types of evaluations were conducted for tactical ground vehicles and equipment. In one evaluation, performance data was collected while a HMMWV was driven on a test track operating on various fuels including SPK blends. (51) Another evaluation had military units at two different locations operating a wide-variety of tactical ground vehicles and/or equipment on SPK blends. (52, 53) A final evaluation focused on assessing performance and durability of bulk water and fuel distribution and handling equipment while operating on SPK blends. (54)

TEST TRACK PERFORMANCE (HMMWV)

This evaluation assessed the performance of a HMMWV 6.5L naturally-aspirated (NA) operating on four fuels in field-like conditions. (51) The fuels used were ULSD, JP-8, FT SPK/JP-8 (50/50 blend), and FT SPK. All fuels contained specified lubricity improver additives to meet fuel specification requirements, with the blended fuel and the FT SPK meeting all other property requirements in the JP-8 specification. The HMMWV accumulated 100 miles unballasted and 100 miles ballasted to 10,300 lbs, for a total of 200 miles per fuel. The test route used for the evaluation, at the Southwest Research Institute campus, included a vehicle test track loop with on- and off-road portions, and a total elevation change of 100 feet over the entire route. Figures 3 and 4 show the map route and elevation change. (51)

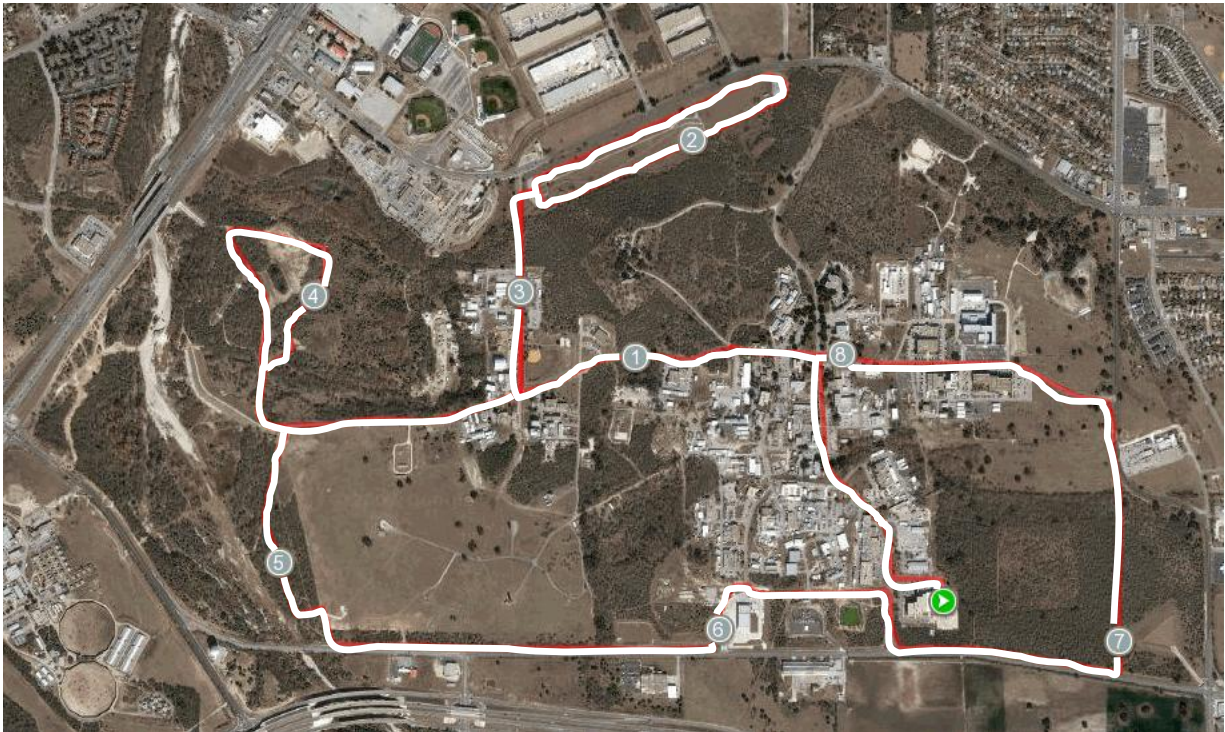


Figure 3 – Driving Route on SwRI Campus

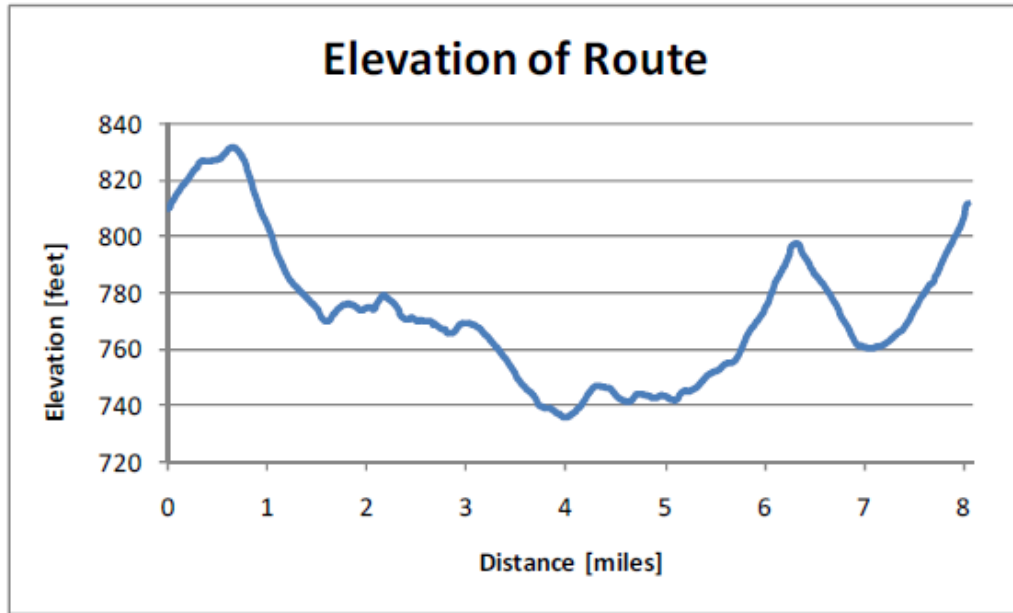


Figure 4 – Elevation Change of Driving Route on SwRI Campus

The HMMWV was equipped for measurement of engine smoke, emissions, operating conditions, and vehicle dynamics. The typical procedure for the 200 mile cycle was as follows (51):

Day 1

- Fill with test fuel
- Drive 100 miles unballasted
- Measure fuel consumed
- Perform acceleration tests for emissions unballasted
- Ballast to 10,300 lbs
- Perform acceleration test with emissions

Day 2

- Perform engine start tests
- Refill with test fuel
- Drive 100 miles ballasted
- Measure fuel consumed
- Perform smoke tests
- Take oil samples

TWV PILOT FIELD DEMONSTRATION

This pilot field demonstration of tactical wheeled vehicles (TWV) was conducted at Fort Bliss for a period of one year utilizing a 50%:50% volumetric blend of FT SPK and JP-8. (52) The main intent of this demonstration was to introduce synthetic blend fuels to the end user during their every day routine to build awareness and acceptance of the fuel blend. Representative vehicles from the Army's tactical vehicle fleets were included in the demonstration and divided into two groups: test vehicles and control vehicles. Test vehicles ran on the FT SPK/JP-8 blend and control vehicles ran

on standard JP-8. Table 13 provides a summary of the vehicles and vehicle count for the demonstration.

Table 13 – TWV Pilot Field Demonstration Vehicle Matrix

Vehicle Nomenclature	Model Number	Vehicles	
		Test	Control
1¼ Ton HMMWV Utility	M998A2	3	1
2½ Ton LMTV Cargo	M1078	6	7
5 Ton Truck Cargo	M925A2	5	4
5 Ton MTV Cargo	M1083A1	5	5
5 Ton FMTV Wrecker	M1089A1	1	1
10 Ton HEMTT Tanker/Wrecker	M978/M984	1	1
22 Ton Line Haul	M915A4	7	4

The vehicles were assigned to the same unit so that both groups were operated under the same duty cycles, which were comprised of the unit's normal missions and training activities. In order to avoid cross contamination of the fuels, fueling areas were set-up at opposite ends of the motor pool with the different fuels, and the test vehicles were marked with fluorescent orange fuel caps and markers in the windshields. Prior to the demonstration, inspections were conducted on each vehicle's fuel lines and fuel-wetted components to check for any leaks, along with smoke opacity readings, and start of test odometer readings. During the demonstration the following procedure was used for recording data:

- Odometer mileage readings from each test and control vehicle conducted on a bi-monthly basis
- DA Form 3642 (Daily Issues of Petroleum Products) for each vehicle maintained by the Unit POL personnel and were collected on a daily basis
- Quarterly physical inspections of fuel-wetted components and smoke opacity readings on all vehicles
- Fuel sampling from of all test vehicles, seven randomly selected control vehicles, and both fuel storage tanks on a bi-monthly basis

DEMONSTRATION AT CAMP GRAYLING

A total of 10,000 gallons of the HEFA SPK/JP-8 fuel blend was provided for the purpose of conducting a demonstration on a non-interference basis to the mission of the Joint Maneuver Training Center at Camp Grayling, Michigan. (53) Army Michigan National Guard (MING) units operated a variety of tactical ground vehicles and other equipment they brought with them to Camp Grayling on the candidate JP-8 drop-in fuel as they performed their annual summer training exercises.

PETROLEUM AND WATER SYSTEMS (PAWS) PILOT FIELD DEMONSTRATION

This pilot field demonstration encompassed two evaluations. (54) One evaluation focused on various components such as pumps, hoses, valves, couplers, adapters, and pipe sections that comprise the typical PAWS bulk fuel and water distribution and handling equipment. The other evaluation focused on a specific system, the Advanced Aviation Forward Area Refueling System (AAFARS).

PAWS Distribution and Handling Equipment: Two PAWS pump / engine assemblies were selected for this evaluation on the basis of unique sub-systems they employ for fueling and cooling compared to other military ground equipment. The evaluation was set-up to determine their ability to maintain an acceptable level of operation when using SPK fuel blends. The two pumps identified are listed in Table 14. Two recirculation loops were set-up, each appropriately sized for the pumps involved. Also included in each recirculation loop were at least one each of the commonly used (4-inch) suction hoses, discharge hoses, butterfly valves, couplers, adapters, and straight pipe sections. Each pump / engine assembly was subjected to a 400 hour durability test while operating on the FT SPK/JP-8 blend with water in the recirculation loop. The loops were designed with instrumentation to measure pump outlet flow rate, pump outlet pressure, fuel supply pressure, and temperatures of the recirculation loop fluid (water), fuel and air (inlet to engine). The complete PAWS Pump / Engine Durability Test Matrix is provided in Table 15.

Table 14 – Selected Pump / Engine Assemblies from Petroleum and Water Systems

Identified Pump	Engine Model	Engine Manufacturer
350 GPM	V3300	Kubota
600 GPM	BF4L914	Deutz

Table 15 – Pump / Engine Assemblies Durability Test Matrix for Petroleum and Water Systems

Test Cycle	Pump	Full Rated Condition	Flow Rate Tolerance	Temperature Conditions
• 8 hrs minimum daily	350 GPM	350 gpm at 275 ft pressure head	within 5%	• 100°F – 120°F air^{1, 2} • 100°F – 105°F fuel inlet to engine
• 15-30 minutes allowances for warm-up and cool-down	600 GPM	600 gpm at 350 ft pressure head	within 5%	
• 400 hrs total test cycle				

Table Footnotes:

1. Pump / engine assembly placed in an exhaust-ventilated, insulated box to capture waste heat to increase air temperature to 100°F minimum, with controls to limit air temperature within box to 120°F maximum.
2. Deviation of box internal air temperature allowed during engine warm-up time.

Advanced Aviation Forward Area Refueling System (AAFARS): This evaluation utilized a recirculation loop set-up with an AAFARS 265 GPM pump / engine assembly using components from the AAFARS and from the Fuel System Supply Point (FSSP). A list of all of the components associated with the AAFARS and the FSSP are provided in Appendix C; as many of these components as possible, but not necessarily all, were incorporated into the test set-up. The recirculation loop was designed to maximize exposure of the components to the FT SPK/JP-8 fuel blend that circulated through the loop during the test. A 400-hour durability test was conducted, operating the pump / engine assembly on the fuel blend and circulating the fuel blend through the loop. Instrumentation was incorporated to obtain pump outlet flow rate, pump outlet pressure, and testing fluid temperature.

IV. RESULTS

Numerous reports and technical papers document the results of the TRL 1-7 evaluations as shown in Section VII (References). The most notable references and a short description of the results they contain are summarized in this section (IV). The actual volume and complexity of results is too immense to detail within this report. However, in Section V (Discussion), the most important results are summarized to accompany the discussion of their significance.

A. Fuel Evaluations (TRL 1-4)

Since the fuels being qualified are aviation-grade fuels, many military and commercial aviation stakeholders including the Air Force, Navy, Boeing, Pratt and Whitney, Rolls-Royce, GE Aviation and others conducted the vast majority of the TRL 1-4 work which TARDEC leveraged for the Army ground systems qualification work. However, TARDEC did conduct some additional fuel testing to evaluate properties that are of specific concern to compression ignition (CI) engines. These tests were primarily to determine cetane number and fuel lubricity. In addition, TARDEC conducted some material compatibility testing for elastomers specifically identified in Army tactical ground vehicle fuel systems.

Several reports and technical papers document the results of TRL 1-4 evaluations as shown in Section VII (References). A few of the most notable references and their significance are summarized below. The results from these references will be used in Section V (Discussion) to develop and support the statements in Section VI (Conclusions and Recommendations).

Reference (23): This Coordinating Research Council (CRC) report compares the properties and characteristics of five different FT SPK/jet fuel blends (50/50), each containing a unique SPK blending stock, with one another and with petroleum-based Jet A, Jet A-1 or JP-8 fuel. As stated in the Executive Summary of this report, “The study was requested by the aviation fuel community to provide technical support for the acceptance of synthetic paraffinic kerosene (SPK) derived from synthesis gas as blending streams up to 50%(v) in fuel specifications for aviation turbine fuel.”

Reference (27): This TARDEC report studies the lubricity and cetane number properties of 50%(v) blends of SPK and JP-8. Tables 1-7 in this report provide lubricity test results, while Table 10 provides the cetane number test results.

Reference (30): This report issued by the Air Force Research Laboratory (AFRL) provides information on specification and FFP properties of various SPK blends. The data in this report supported Air Force certification of SPK/JP-8 blends (HEFA) and also ASTM Research Reports in support of commercial certification for SPK/jet fuel blends (HEFA). Of note is that cetane number (derived), kinematic viscosity at 40°C, and lubricity properties for several different SPK blends are provided in several tables throughout the report.

The Army Public Health Command (APHC) is completing a toxicity assessment for SPK blends. The expectation is that APHC will issue an Army toxicity clearance for the SPK blends by the end of September 2013.⁸

B. Fuel Injection System Evaluations (TRL 5)

Stanadyne Rotary Distributor Fuel Injection Pump

References (17) (34): These TARDEC reports provide results from test rig evaluation of the Stanadyne Rotary Distributor Fuel Injection Pump to determine its durability when operating on SPK blends. Testing included diesel fuel and Jet A-1 fuels to provide a baseline for comparison with the results of the SPK blend tested. Table 5 in Reference 33 is a summary of the results for testing at elevated temperature.

⁸ Personal communication, 27 June 2013, between N. Hubble-TARDEC and W. McCain-APHC

High Pressure Common Rail

References (35) (36) (37): These TARDEC reports provide the results from test rig evaluation of three different high pressure common rail fuel injection systems to determine their durability when operating on SPK blends at elevated temperature.

C. Engine Evaluations (TRL 6)

Cetane Window

Reference (38): This TARDEC report provides the results from a study done using test fuels having a wide distribution of various properties such as cetane number, density, energy density, and bulk modulus. The study evaluated the impacts of operating the GEP 6.5LT and Caterpillar C7 engines on these fuels to better understand the relationship between fuel properties and engine performance.

Performance and Durability

GEP 6.5LT

References (39) (40): These TARDEC reports provide the results from engine dynamometer testing, per the NATO 400-hour protocol, of the GEP 6.5L turbo engine when operating on SPK blends, FT and HEFA, respectively, and on a JP-8 baseline for comparison. These results are for testing conducted at ambient temperature.

Caterpillar C7

References (41) (42): These TARDEC reports provide the results from engine dynamometer testing of the Caterpillar C7 engine when operating on SPK (FT, neat) per the TWV 210-hour protocol (2×) and on the SPK blend (FT) per the NATO 400-hour protocol, respectively, and on a JP-8 baseline for comparison. These results are for testing conducted at elevated temperature.

DDC 8V92TA

Reference (43): This TARDEC report provides the results from engine dynamometer testing, per the NATO 400-hour protocol, of the DDC 8V92TA engine when operating on the SPK blend (FT) and on a JP-8 baseline for comparison. These results are for testing conducted at ambient temperature.

Cummins VTA-903T

Reference (44): This TARDEC report provides the results from engine dynamometer testing, per the NATO 400-hour protocol, of the Cummins VTA-903T engine when operating on the SPK blend (FT) and on a JP-8 baseline for comparison. These results are for testing conducted at elevated temperature.

Navistar MaxxForce 9.3D

Reference (45): This TARDEC report provides the results from engine dynamometer testing, per the NATO 400-hour protocol, of the Navistar Maxxforce 9.3D engine when operating on the SPK blend (FT) and on a JP-8 baseline for comparison. These results are for testing conducted at elevated temperature.

Ford 6.7L Powerstroke

References (46) (47): This TARDEC report and GVSETS paper provide the results from engine dynamometer testing, per the TWV 210 hour protocol (slightly modified), of the Ford Powerstroke engine when operating on SPK (neat, FT) and SPK blend (FT), and on diesel (ultra-low sulfur) and JP-8 as baselines for comparison. These results are for testing conducted at elevated temperature.

D. Ground Vehicle and Equipment Evaluations (TRL 6-7)

Tactical Generator Sets Side-by-Side Operation

Reference (48): This TARDEC report provides the results from an evaluation that compared side-by-side operation of three 10-kW tactical generator sets while operating on various fuels including SPK/JP-8 blend, SPK, JP-8 and diesel (ultra-low sulfur).

Tactical Generator Sets Performance and Durability

References (49) (50): These TARDEC reports provide the results from an evaluation of the performance and durability of tactical generator sets, of sizes ranging from 2-kW to 100-kW, while operating on SPK/JP-8 blend fuel. The evaluation of performance is only partially complete as of the writing of this report.

Test Track Performance (HMMWV)

Reference (51): This TARDEC report provides the results from an evaluation of the performance of a HMMWV while operating on a test track using SPK/JP-8 blend, SPK, JP-8 and diesel (ultra-low sulfur) fuels.

Tactical Wheeled Vehicle (TWV) Pilot Field Demonstration

Reference (52): This TARDEC report provides the results of a one year-long pilot field demonstration of various tactical wheeled vehicles operating on SPK/JP-8 blend fuel as conducted on a non-interference basis by the 6th ADA Brigade at Fort Bliss, TX.

Tactical Ground Vehicles and Equipment Demonstration

Reference (53): This TARDEC report provides the results of a demonstration of SPK/JP-8 blend fuel used in various tactical ground vehicles and other equipment as conducted on a non-

interference basis by selected Michigan National Guard units during annual summer training exercises at the Joint Maneuver Training Center at Camp Grayling, Michigan.

Petroleum and Water Systems (PAWS) Pilot Field Demonstration

Reference (54): This TARDEC report provides the results, as of writing of this report, for two evaluations. One evaluation focused on assessing the performance of the various components (pumps, hoses, valves, couplers, adapters, and pipe sections) found in PAWS equipment for bulk fuel and water when operating with SPK blends. Part of this evaluation included testing of the durability of two selected pump / engine assemblies. The other evaluation focused on assessing the performance and durability of a specific system, the Advanced Aviation Forward Area Refueling System (AAFARS) when operating with SPK blends.

V. DISCUSSION

A. Fuels

Synthetic Paraffinic Kerosene (SPK) Blending Stocks

Neat Synthetic Paraffinic Kerosene (SPK) was found to be comprised nearly entirely of hydrocarbon compounds with minimal if any heteroatoms (compounds containing nitrogen, oxygen, sulfur, etc.) and therefore it is an ideal fuel blending stock. The various hydrocarbon molecules found in SPK (FT or HEFA) are already present in petroleum-derived JP-8. However, SPK may lack aromatic compounds and/or trace compounds found in petroleum-derived JP-8. These differences in chemical composition give SPK unique properties that differ in some respects from petroleum-derived JP-8. Neat SPK is not acceptable as an aviation fuel because of these property differences. However, when SPK is blended up to 50% by volume with petroleum-derived JP-8, it has been determined to be an acceptable aviation fuel and certified for use in commercial and military (Air Force) aircraft.

SPK blending stocks must meet the property requirements called out in the JP-8 specification. These are found in Appendices A and B, Tables A-I and B-I, of the JP-8 specification for FT SPK and HEFA SPK, respectively. These requirements are more comprehensive and stringent than those for petroleum JP-8. For instance, the allowed ranges of density, sulfur content, and aromatics are tighter than for petroleum JP-8. In addition, there are limits for cycloparaffin content and for distillation temperature span, at 10% and 90% volume recovered, for SPK whereas these limits do not exist for petroleum JP-8. These additional requirements ensure the chemical and physical properties of the SPK are acceptable for use of the SPK as an aviation-grade fuel blending stock.

The additional requirements for SPK as a blending stock for aviation-grade fuel do not include specific requirements for use in ground vehicles and equipment. TARDEC proposed that the JP-8 specification include two additional requirements for SPK, one for high temperature viscosity (at 40°C) and the other for cetane number, both requirements for diesel fuel. Ultimately, a requirement for cetane number (derived) was introduced into the JP-8 specification for the SPK blends (minimum 40), rather than the SPK blending stock. This approach ensures an acceptable ignition/combustion quality fuel for ground vehicles and equipment. Although the requirement for high temperature viscosity was not introduced into the JP-8 specification, SPK blends will still be acceptable for use

as a ground fuel. The impact of this property will be discussed further in the next sub-section of this report (SPK/JP-8 Blends).

SPK/JP-8 Blends (FT, HEFA)

The physical and chemical properties of blends of up to 50% by volume of SPK with petroleum-derived JP-8 are, for all practical purposes, indistinguishable from those of petroleum-derived JP-8. The SPK blends are, in fact, drop-in fuels that can replace petroleum JP-8. A discussion of how the requirements for these blends are incorporated into the JP-8 specification is provided below. This is followed by a comparison between some of the more important properties for ground vehicles and equipment of blends and petroleum-derived JP-8.

REQUIREMENTS FOR SPK BLENDS IN THE JP-8 SPECIFICATION

The requirements for blends of SPK with petroleum JP-8 are detailed in several places in the JP-8 specification and are summarized in the following paragraphs.

Section 3.1.1, Synthesized Materials: In this section the limitation for no more than 50% by volume of SPK in the finished fuel is stated. The blended SPK/JP-8 fuel must meet the requirements in Table I. The FT SPK and HEFA SPK blending stocks, as well as the fuel blends with JP-8 created using them, must also meet the requirements in Appendix A.2 and B.2, respectively. The requirements for the chemical and physical properties that petroleum JP-8 has always had to meet are shown in Table I. Thus the blends have to meet the petroleum JP-8 requirements plus the additional requirements in Appendices A or B. In 3.1.1 the requirements for additives in the finished fuel containing SPK are also stated; these include antioxidant, as well as static dissipater additive, corrosion inhibitor/lubricity improver, and fuel system icing inhibitor that are mandatory for all JP-8 whether it contains SPK or not.

Table I, Chemical and Physical Requirements and Test Methods: This table provides the requirements for the chemical and physical properties of JP-8 fuel, as well as the acceptable test methods for determining these properties. These requirements apply to all JP-8, including JP-8 containing synthesized materials, i.e., JP-8 containing FT SPK or HEFA SPK blending stock.

Appendix A, Fischer-Tropsch Synthesized Paraffinic Kerosene: This section provides requirements for the FT SPK blending stock as well as for FT SPK blends. In particular, Table A-II provides the chemical and physical property requirements that the FT SPK blends must meet in addition to the property requirements in Table I that all JP-8, including FT SPK/JP-8 blends, is required to meet. Note that a requirement for a minimum cetane number (derived) for FT SPK blends is found in Table A-II. This requirement helps ensure that the FT SPK blends will have an acceptable ignition/combustion quality when used as a fuel in ground systems with compression ignition engines.

Appendix B, Hydroprocessed Esters and Fatty Acids Synthesized Paraffinic Kerosene: This section provides requirements for the HEFA SPK blending stock as well as for HEFA SPK blends. In particular, Table B-II provides the chemical and physical property requirements that the HEFA SPK blends must meet in addition to the property requirements in Table I that all JP-8, including HEFA SPK/JP-8 blends, is required to meet. Note that a requirement for a minimum

cetane number (derived) for HEFA SPK blends is found in Table B-II. This requirement helps ensure the HEFA SPK blends will have an acceptable ignition/combustion quality when used as a fuel in ground systems with compression ignition engines.

PROPERTIES IMPORTANT TO THE USE OF FUELS SPECIFIED BY MIL-DTL-83133 IN GROUND VEHICLES AND EQUIPMENT

There are several properties that are important for fuels used in ground vehicles and equipment as they can impact performance (e.g., power, torque, fuel consumption) and durability of compression ignition engines. These properties will be discussed in the following paragraphs to describe how the SPK blend properties compare to petroleum JP-8 properties.

Density: SPK blends must meet the same specification requirements for density as petroleum JP-8. Furthermore, SPK blending stocks also must meet a separate density requirement. The SPK blending stocks and SPK blends have been shown to meet both of these requirements. These requirements are shown in Table 16.

Table 16 – Density Requirements for JP-8, SPK, and SPK/JP-8 Blends

Property	Limits		Limits Apply to:		
	Min	Max	JP-8	Blends of SPK/JP-8	SPK
Density, kg/L at 15°C	0.751	0.770			X
	0.775	0.840	X	X	

Since SPK blending stock has a density lower than petroleum JP-8, the weighted mean density for the blended JP-8 will decline slightly as increasing volumes to SPK are blended with petroleum JP-8 up to the 50% limit.

A TARDEC study of this topic was conducted using the actual property data recorded for all JP-8 batches procured worldwide during 2009. The study assumed the worst case or lowest allowable density and aromatic content for SPK which is 0.751 kg/L and 0% by volume, respectively.⁹ This demonstrated that the worldwide weighted mean density for JP-8 would have been 3.1% lower if all the JP-8 that year contained the maximum possible volume of SPK while still meeting both the minimum density and minimum aromatic content requirements for JP-8 containing SPK.

A review of density data for all JP-8 batches procured worldwide for DoD use in the years from 2007 through 2012, as recorded in PQIS¹⁰, found the lowest density was 0.775 kg/L. This

⁹ Study conducted by N. Hubble, TARDEC Fuels and Lubricants Technology Team

¹⁰ The Petroleum Quality Information System (PQIS) is managed by the Quality/Technical Support Office of the Defense Logistics Agency Energy. PQIS data is published in annual reports available via e-mail request to pqis@dla.mil.

happens to be the lowest density allowed by the JP-8 specification. This data is shown in Table 17, as well as density data for various batches of SPK blending stocks and SPK blends. This data shows that the lowest densities for each year from 2007 through 2012 ranged from 0.775 kg/L to 0.787 kg/L. The range of density values for the SPK blends shown in this table are similar, ranging from 0.774 kg/L to 0.798 kg/L. An important point is that the blend data represents the “worst case” densities as these are all blends used in qualification testing which are blends containing the maximum possible volume of SPK at 50% of the total volume of the blend with JP-8. In all cases, for testing and implementation, the SPK blends will be required to meet or exceed the minimum density allowed by the JP-8 specification of 0.775 kg/L. (Table 16)

Table 17 – Density Data for JP-8, SPK, and SPK/JP-8 Blends¹

Description of Kerosene Sample	Density (kg/L) [ASTM D1298, D4052]	Reference, Page Numbers
JP-8	0.786	PQIS 2012 Annual Report, 35
JP-8	0.781	PQIS 2011 Annual Report, 37
JP-8	0.785	PQIS 2010 Annual Report, 33
JP-8	0.775	PQIS 2009 Annual Report, 27
JP-8	0.787	PQIS 2008 Annual Report, 29
JP-8	0.784	PQIS 2007 Annual Report, 29
SPK (FT)	0.755	21, 68
SPK (FT)	0.756	24, 9
SPK (FT)	0.755	52, 13
SPK (HEFA)	0.762	26, 66
SPK (HEFA)	0.775	26, 114
SPK (HEFA)	0.750	28, 155
SPK Blend (FT)	0.774 ²	21, 68
SPK Blend (FT)	0.782	24, 9
SPK Blend (FT)	0.781	52, 13
SPK Blend (FT)	0.788	39, 50
SPK Blend (HEFA)	0.783	26, 66
SPK Blend (HEFA)	0.798	26, 114
SPK Blend (HEFA)	0.777	28, 155
SPK Blend (HEFA)	0.786	40, 30

Table Footnotes:

1. The densities of the JP-8 shown in this table are the minimum densities recorded for batches of JP-8 purchased for DoD use during each year from 2007 through 2012; these are not reflective of the densities of JP-8 used to create the blends shown in this table.
2. Although this value of 0.774 kg/L is just below the minimum density required per the JP-8 specification of 0.775 kg/L, this batch of fuel was allowed for use during qualification testing.

Some engines have fuel injection systems (FIS) that are sensitive to fuel density. Variations from the FIS design basis or calibration density may result in less than optimal performance.

The possibility of less than optimal performance is already a reality for compression ignition engines used by the military because the engines are operating on JP-8 rather than diesel fuel.

Volumetric Energy Density: SPK blends must meet the same specification requirement for gravimetric energy density as petroleum JP-8. The studies described herein demonstrate that SPK blends meet this requirement. The requirement is for a minimum gravimetric energy density of 42.8 MJ/kg, as detailed for the limit (lower) for net heat of combustion in the JP-8 specification. This same requirement also applies to SPK blending stocks.

Volumetric energy density can be calculated from a given fuel's density and gravimetric energy density. This calculation was done as part of the same TARDEC study described in the prior paragraph for the discussion on density. The study used actual gravimetric energy density determined for one FT SPK which was 43.8 MJ/kg. This was slightly higher than the minimum allowed in the JP-8 specification of 42.8 MJ/kg. This study showed that the worldwide weighted mean energy density (volumetric, calculated) for JP-8 would have been 2.5% lower if all the JP-8 that year contained the maximum possible volume of SPK while still meeting both the minimum density and minimum aromatic content requirements for JP-8 containing SPK. The shift in energy density of -2.5% for SPK would require that SPK blending stock replace 46% by volume of the JP-8 procured worldwide that year (2009), an amount of nearly 1 billion gallons. The results from a separate, similar study conducted by the Air Force are in good agreement with the TARDEC study. (55) The Air Force study looked at SPK (not a blend), and found the SPK to have a 4.7% lower energy density (volumetric, calculated) as compared to the weighted mean for JP-8 batches procured worldwide in 2004. This difference would be cut to only -2.2% assuming the same composite volume replacement or blending ratio of JP-8 with SPK of 46%.

As there are regional variations in the properties of petroleum JP-8 fuel, stemming from the source of crude and refinery configurations in any given region, the shift in energy density will also vary somewhat by region. The study showed that the shift in energy density for any given batch of JP-8 was as little as a -1.8% for Petroleum Administration for Defense Districts (PADD) Region 6 (Middle East) and as much as -4.4% for Region 3 (U.S. Gulf Coast). The batch of FT SPK/JP-8 blend with the maximum shift in energy density (-4.4%) still had a higher energy density than 98% of the other blended batches, and even than 22% of neat JP-8 batches.

Since ground vehicles have a fixed volume of on-board fuel capacity, a decrease in fuel volumetric energy density will translate to a decrease in the range possible for that vehicle before refueling. However, as there are several factors that can impact the fuel consumption of a vehicle besides fuel energy content (e.g., driver behavior, terrain, engine performance sensitivity to other fuel properties such as cetane number, etc.), it is not possible to state definitively what actual decrease in range might result from a given decrease in the fuel energy density. Given the small difference in energy content between JP-8 and SPK/JP-8 blends containing the maximum allowable SPK content, and based on prior experience that bulk fuel consumption is dependent on vehicle and equipment mix and usage, it is unlikely that average vehicle fuel consumption (across fleet) would be statistically any different for SPK/JP-8 blends than for petroleum JP-8. (56)

Cetane Number: The petroleum JP-8 specification has no requirement for cetane number, only a requirement for reporting of the cetane index of the fuel. TARDEC sought and was successful in adding an Army requirement into the JP-8 specification to limit the cetane number (derived) to a minimum of 40 for SPK blends. This ensures that SPK blends will have an acceptable ignition quality allowing reliable starting of compression ignition engines, especially cold engines. The cetane limit will also provide SPK blends with good combustion characteristics to prevent damage to components from extreme rate of pressure rise events. Even more favorable is the fact that most SPK has been shown to have a desirable cetane number (derived), typically of above 50. By blending in SPK with petroleum JP-8, the majority of the blended fuel will have an improved cetane number compared to typical petroleum JP-8. These statements are supported by the data shown in Table 17. This data is a representative set of data drawn from the various references as cited previously within this report that provide extensive data for cetane number of SPK, SPK blends and petroleum JP-8.

Table 18 – Cetane Number Data for JP-8, SPK, and SPK/JP-8 Blends

Description of Kerosene Sample	Cetane Number¹ [ASTM D6890]	Reference, Page Numbers
JP-8	45	27, 16
JP-8 ²	45	38, A-2
JP-8	50 ³	43, 21
JP-8	49	45, A-3
JP-8 ²	39	52, 13
SPK (FT)	60	27, 16
SPK (FT)	58	52, 13
SPK (HEFA)	54	28, 158
SPK (HEFA)	59	38, A-2
SPK Blend (FT)	52	27, 16
SPK Blend (FT)	47	39, 50
SPK Blend (FT)	47	43, 21
SPK Blend ² (FT)	48	52, 13
SPK Blend ² (HEFA)	51	28, 147
SPK Blend (HEFA)	49	28, 158
SPK Blend (HEFA)	48	45, A-4
SPK Blend (HEFA)	54	53, 16

Table Footnotes:

1. The values in this table are for Derived Cetane Number using the Ignition Quality Tester (IQT) apparatus specified in ASTM D6890.
2. Jet A or Jet A with JP-8 additives was used rather than JP-8 or Jet A-1 or Jet A-1 with JP-8 additives.
3. This value is drawn from the original laboratory results reported in Work Order 00738 for fuel sample FL-13513-10; the value found in the noted reference was in error.

There is one particular conversion process at a single manufacturing plant, a very unique one, which does produce a FT SPK with a very poor cetane number of well under 40. However,

discussion with the supplier of this particular FT SPK indicated this process was not likely to be replicated in any conversion plants constructed in the future. Even so, it was still thought advisable to add this requirement into the JP-8 specification, particularly as it sets a precedent in terms of a cetane requirement for other future alternative fuels proposed as drop-in JP-8 fuels entering into DoD qualification and certification efforts.

Volatility: SPK blends must meet the same specification requirements for volatility as petroleum JP-8 does. The SPK blends have been shown to meet these requirements. Furthermore, SPK blending stock and SPK blends must meet volatility requirements in addition to the standard petroleum JP-8 requirements. The SPK blending stocks and SPK blends have been shown to meet these requirements. The key volatility requirements are in terms of limits on distillation temperatures at volume percent sample recovered. Table 18 below is a summary of the requirements.

Table 19 – Selected Volatility Requirements for JP-8, SPK, and SPK/JP-8 Blends

Distillation Property: Temperature or Temperature Gradient, °C	Limits³		Limits Apply to:		
	Min	Max	JP-8	Blends of SPK/JP-8	SPK
at 10% recovered		205	X	X	X
at Final boiling point		300	X	X	X
at 50% recovery gradient ¹ [T ₅₀ – T ₁₀]	15			X	
at 90% recovery gradient ² [T ₉₀ – T ₁₀]	22 (SPK); 40 (blends of SPK/JP-8)			X	X

Table Footnotes:

1. The temperature difference between the temperature that demarks the 10 percent recovered point and the temperature that demarks the 50 percent recovered point.
2. The temperature difference between the temperature that demarks the 10 percent recovered point and the temperature that demarks the 90 percent recovered point.
3. Distillation property criteria are specified in ASTM D86 scale units.

As shown in Table 18, there are additional requirements for SPK blending stocks and SPK blends to limit the temperature gradients between the temperature at 10% recovery point and the 50% and/or 90% recovery point. These limits are a means of controlling the volatility of the SPK blends so that it remains similar to petroleum JP-8. Typical petroleum jet fuel has a smooth and continuous distillation curve as a result of a full complement of hydrocarbon compounds, from about 8 to 16 carbon atoms in the molecular backbone ($\sim C_8-C_{16}$), with boiling points that are distributed across the full curve. A severely flattened distillation curve, or one that is not smooth and continuous, would be indicative of a fuel with a significantly different chemical composition from that of petroleum jet fuel. It is uncertain whether such a fuel, which would have unique properties, would be an acceptable drop-in replacement for JP-8.

The various references cited previously within this report provide extensive data for the volatility of SPK, SPK blends and petroleum JP-8, including full distillation curves. A representative subset of this data that shows the distillation temperature gradients (T₉₀-T₁₀ and T₅₀-T₁₀) is

summarized in Table 18. As the data in this table shows, the volatility for SPK and SPK blends is similar to JP-8. If anything, this data actually shows distillation temperature gradients for some SPK and SPK blends can be somewhat greater than for some petroleum JP-8. This is good because it means SPK blending stocks having a wide distribution of hydrocarbon compounds across the aviation kerosene boiling range, rather than a narrow distribution, are produced from these SPK conversion processes.

Table 20 – Selected Volatility Data for JP-8, SPK, and SPK/JP-8 Blends

Description of Kerosene Sample	Distillation Temperature Gradients (°C)		Reference, Page Numbers
	T ₅₀ - T ₁₀	T ₉₀ - T ₁₀	
JP-8	33	80	24, 9
JP-8	16	42	24, 10
JP-8	26	63	26, 65
JP-8 ¹	18	45	28, 241
JP-8	25	66	29, D
JP-8	20	48	45, A4-7
JP-8	28	81	51, 2
SPK (FT)	--	89	24, 9
SPK (FT)	--	83	51, 2
SPK (HEFA)	--	85	26, 65
SPK (HEFA)	--	79	28, 154
SPK Blend (FT)	36	83	24, 9
SPK Blend (FT)	30	67	24, 10
SPK Blend (FT)	31	85	51, 2
SPK Blend (HEFA)	33	77	26, 65
SPK Blend ¹ (HEFA)	22	76	28, 143
SPK Blend (HEFA)	29	75	28, 154
SPK Blend (HEFA)	30	86	45, A4-4

Table Footnotes:

1. Jet A or Jet A with JP-8 additives was used rather than JP-8 or Jet A-1 or Jet A-1 with JP-8 additives.

Volatility is an important fuel parameter for compression ignition engines, particularly in regards to ignition, combustion and fuel atomization. The military has been operating its ground vehicles and equipment on JP-8 for over two decades. The fact that the SPK blends have similar volatility characteristics to JP-8, and the requirements in the JP-8 specification ensure this, provides a clear indicator that the risk of issues pertaining to engine performance or durability attributable to fuel volatility impacts is low. Even so, as part of evaluating the impacts of fuel properties (SPK blends) on engine performance and durability, several engine dynamometer tests were conducted to confirm this assessment and these results are discussed in a later section of this report.

Viscosity at High Temperature: The petroleum JP-8 has no specification requirement limiting viscosity at high temperature. On the other hand, diesel fuel specifications typically have a viscosity at high temperature requirement. There is a requirement in the ASTM D975 diesel fuel specification for a minimum kinematic viscosity at 40°C of 1.3 mm²/s and 1.9 mm²/s for No. 1-D and No. 2-D grades, respectively. In the ASTM D975 specification, Section X1.6, it states that “For some engines it is advantageous to specify a minimum viscosity because of power loss due to injection pump and injector leakage.” Knowing that some engines used in military ground vehicles have fuel injection systems that are susceptible to this issue, TARDEC sought, but was unsuccessful, in getting an Army requirement into the JP-8 specification to limit the kinematic viscosity at 40°C for SPK to a minimum of 1.3 mm²/s. (56) Since, on a worldwide basis, JP-8 viscosity at 40°C has been reported to be as low as 1.1 mm²/s, this additional requirement would have helped ensure a viscosity quality for SPK blends no worse than for petroleum JP-8. (57)

Despite the fact the kinematic viscosity at high temperature is not controlled in the JP-8 specification, introducing SPK blends (FT, HEFA) into use for ground engines does not appear to present a significant issue. There is an accumulation of data on the kinematic viscosity at 40°C for SPKs, as well as for SPK blends, as provided in the various references previously cited in this report. A representative subset of this data is summarized in Table 20. As the data in this table shows, the kinematic viscosity at 40°C for SPK and SPK blends is similar to JP-8. Furthermore, there is some additional elevated temperature data, for viscosity above 40°C and more reflective of higher fuel temperatures seen under-the-hood in desert-like operating conditions, that shows the viscosity versus temperature function for SPK blends is within the baseline for jet fuel. An example of some of this data is provided in Figure 5 which is drawn from the TARDEC report of dynamometer testing completed with the GEP 6.5LT engine operating on HEFA SPK blend. (28)

Table 21 – High Temperature Viscosity Data for JP-8, SPK, and SPK/JP-8 Blends

Description of Kerosene Sample	Kinematic Viscosity at 40°C (mm²/s)^{1, 2} [ASTM D445]	Reference, Page Numbers
JP-8	1.1	21, 71
JP-8	1.3	30, 23
JP-8	1.4	30, 23
JP-8	1.1	34, 4
JP-8	1.4	39, 50
JP-8	1.4	43, 21
JP-8	1.5	45, A4-3
SPK (FT)	1.2	28, 51
SPK (FT)	1.4	21, 71
SPK (HEFA)	1.1	28, 155
SPK (HEFA)	1.5	26, 115
SPK Blend (FT)	1.2	21, 71
SPK Blend (FT)	1.2	43, 21
SPK Blend (FT)	1.3	39, 50
SPK Blend (HEFA)	1.2	28, 155
SPK Blend (HEFA)	1.2	30, 26
SPK Blend (HEFA)	1.3	31, 26
SPK Blend (HEFA)	1.3	45, A4-4
SPK Blend (HEFA)	1.4	28, 166
SPK Blend (HEFA)	1.4	30, 26
SPK Blend ³ (HEFA)	1.5	26, 115

Table Footnotes:

1. Some of the viscosity data was reported with two significant figures; these were rounded to one significant figure for inclusion in this summary table.
2. All data shown for JP-8 is based on CONUS samples. Viscosity data for jet fuel will vary to some degree regionally worldwide based on regional differences in petroleum crude oil sources and refinery configurations.
3. Blend with Jet A; all other blends in this table are with JP-8 or Jet A-1.

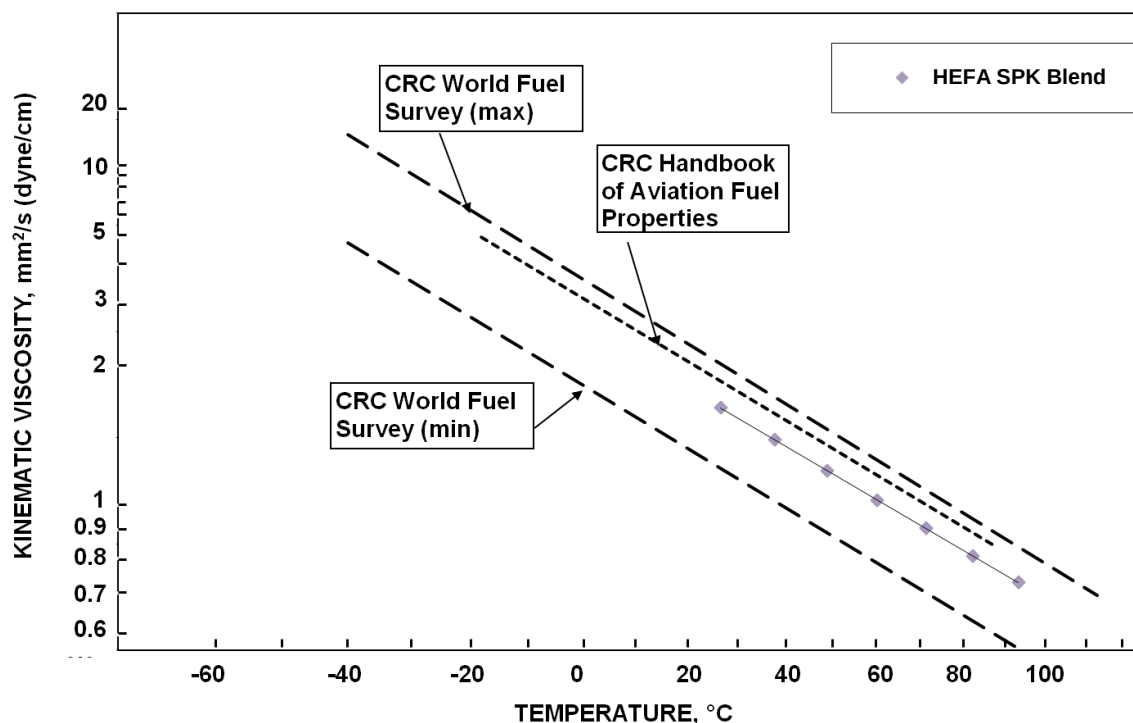


Figure 5 – Viscosity versus Temperature for HEFA SPK Blend and Jet Fuel (28)

Lubricity: SPK blends must meet the same specification requirement for lubricity as petroleum JP-8 does. The SPK blends have been shown to meet this requirement. The JP-8 specification requires that a Corrosion Inhibitor/Lubricity Improver (CI/LI) additive be blended into all JP-8 in accordance with MIL-PRF-25017. All approved CI/LI qualified per MIL-PRF-25017 provide a fuel lubricity of 0.65 mm or less wear scar diameter as determined by the Ball-on-Cylinder Lubricity Evaluator (BOCLE) described by ASTM D5001. There is a significant accumulation of BOCLE lubricity data for SPK blends, as well as for JP-8 provided in the various references previously cited in this report. A representative subset of this data is summarized in Table 18. As the data in this table shows, the BOCLE for SPK blends is similar to JP-8.

Table 22 – Lubricity Data for JP-8, SPK, and SPK/JP-8 Blends

Description of Kerosene Sample¹	Wear Scar Diameter (mm) [ASTM D5001]	Reference, Page Numbers
JP-8	0.51	21, 71
JP-8	0.56	24, 9
JP-8	0.56	24, 10
JP-8 ²	0.53	26, 66
JP-8	0.48	27, 2
JP-8	0.53	30, 25
SPK Blend (FT)	0.50	21, 71
SPK Blend (FT)	0.54	24, 9
SPK Blend (FT)	0.53	24, 10
SPK Blend (FT)	0.48	27, 2
SPK Blend ² (HEFA)	0.56	26, 66
SPK Blend (HEFA)	0.53	30, 27
SPK Blend (HEFA)	0.55	30, 27
SPK Blend ² (HEFA)	0.52	53, 17

Table Footnotes:

1. All samples were treated with approved CI/LI per QPL-25017.
2. Based on Jet A sample with additives per JP-8 specification; all other data shown are for either JP-8 or Jet A-1 with additives per JP-8 specification.

It is important to note that the ASTM diesel fuel specification (D975) also includes a requirement for lubricity. However, the test method specified is not the same as the test method used for JP-8. The High Frequency Reciprocating Rig (HFRR) test method is used for diesel fuel, whereas the BOCLE test method is used for aviation fuel. Prior testing has shown that the HFRR test method is not sensitive to the approved type and treat rate of lubricity improvers required for JP-8. (27) On the other hand, the BOCLE test method is sensitive to the lubricity improvers allowed in JP-8. Even so, since the HFRR test method is of importance to the diesel engine community, there is HFRR data for many of the test fuels and it is found in many of the references of this report. The diesel engine OEMs will continue to warranty engines based on use of fuel meeting diesel fuel lubricity requirements (HFRR).

Bulk Modulus (Fluid Compressibility): The bulk modulus of a fluid is a measure of its resistance to compression. Some engine designs are more sensitive to variations in fuel bulk modulus which can impact fuel injection timing, combustion efficiency, and overall engine performance. (58) The bulk modulus (isothermal) of some alternative and synthetic fuels has been shown to be lower than that of petroleum-based fuels. (59) Data on the bulk modulus (isothermal) of SPK blends has been reported from several studies. (23, 28) An example from one report shows a difference in bulk modulus of -3.1% for a 50/50 blend of FT SPK and JP-8 versus JP-8. (23) The report explains this difference is related to the fact that FT SPK has a lower aromatic content than petroleum JP-8. It is known that aromatic compounds have a higher bulk modulus than do paraffinic compounds, thus the reason for this decrease in bulk modulus when blending FT SPK with JP-8.

Although no fuel specification currently has a requirement for bulk modulus, it is certainly a property of interest for both the aviation and ground vehicle communities. Fuel bulk modulus is a designated “fit-for-purpose” property that must be assessed during qualification of alternative jet fuel for use in commercial and military jet aircraft as it’s an important factor in servomechanisms. (8) More recently proposed candidate drop-in jet fuels, such as Alcohol-to-Jet (ATJ) fuels can have chemical compositions that are quite unique from petroleum jet fuel. (60) It is possible that a specification requirement for bulk modulus might be needed to ensure acceptable levels of performance for equipment operated on drop-in jet fuels. More research in this area is on-going. TARDEC and the staff of the Southwest Research Institute, where the Army has a research facility for fuels and lubricants, have developed a new apparatus capable of determining the bulk modulus (the preferred isentropic value) of a fuel for fuel temperatures as high as 100°C and pressures as high as 30,000 psig. (28) TARDEC wanted an apparatus able to provide data relevant to high-pressure common rail fuel injection systems found in modern diesel engines. Test method development using this apparatus is underway.

Some initial data was generated using the Army’s prototype bulk modulus apparatus after confidence was built that it was providing accurate data. (38) An analysis of this initial data was conducted in terms of what might be proposed as “. . . an acceptable region of isentropic bulk modulus (subject to OEM concurrence)” with respect to an aviation fuel FFP property. (30) The results of that analysis suggested an isentropic bulk modulus of 170,000-210,000 psi (at 30°C, 0 psig) for the “green” range (see MIL-HDBK-510, REF 7). Following this initial data reporting, there was additional work conducted in developing more isentropic bulk modulus data using the Army apparatus, although the data available is still limited. Table 22 provides a sample of this limited data. Note that the bulk modulus of JP-8 is ~180,000-190,000 psi, whereas for the SPK blends it is ~172,000-187,000 psi. One SPK blend shown in Table 22, the one with the lowest value, was not included since it was produced with SPK that does not meet requirements set forth in the JP-8 specification (see Table Footnote 2). Another SPK blend was included, although it was produced with SPK that had a distillation gradient for $T_{90}-T_{10}$ of 21 just missing the minimum requirement of 22. Although there is some overlap in values which suggests that the bulk modulus of the SPK blends will be similar to JP-8, it is also possible that for some SPK blends the bulk modulus will be somewhat lower than that of JP-8. More data needs to be generated on both JP-8 and SPK blends to better quantify this difference and verify the acceptable range.

Table 23 – Isentropic Bulk Modulus Data for JP-8, SPK, and SPK/JP-8 Blends

Description of Kerosene Sample	Isentropic Bulk Modulus at 30°C, 0 psig (psi)	Reference, Page Numbers
JP-8 ¹	181,872	30, 34
JP-8	191,712	30, 34
JP-8 ¹	180,500	38, A-2
SPK (FT)	169,015	31, 404
SPK (FT)	169,283	31, 404
SPK (FT)	152,749 ²	38, A-2
SPK (HEFA)	159,600 ³	30, 34
SPK (HEFA)	169,283	30, 34
SPK (HEFA)	186,209	38, A-2
SPK Blend (FT)	177,706	31, 404
SPK Blend (FT)	179,717	31, 404
SPK Blend (FT)	169,359 ²	38, A-2
SPK Blend (HEFA)	172,710 ³	30, 34
SPK Blend (HEFA)	179,717	30, 34
SPK Blend (HEFA)	187,645	38, A-2

Table Footnotes:

1. Based on Jet A sample; all other data shown are for either JP-8 or Jet A-1.
2. The SPK was waived into use for qualification testing even though it had a density significantly less than the minimum allowed for SPK per the JP-8 specification. Therefore, it is likely this bulk modulus value is lower than what could be expected with SPK that does meet the density requirement.
3. This SPK was reported to have more “light”/low molecular weight (MW) compounds than some other SPKs. A check of the reported T₅₀-T₁₀ span for this SPK revealed a span of 21 which is less than the required minimum T₅₀-T₁₀ span of 22 per the JP-8 specification. The compositional extreme may partially explain the lower bulk modulus.

Additional Properties: There are many other fuel properties, besides those discussed in detail above, that were assessed to complete TRL 1-4 evaluations prior to proceeding with further DoD qualification/certification of SPK blends for use in aircraft, ground vehicles and other equipment. As stated previously, these results are reported in many available documents, only a portion of which are cited herein. These results show that the SPK blends have properties that:

(1) meet all requirements per the JP-8 specification and as summarized for TRL 1-2 evaluations, Appendix A,

(2) meet fit-for-purpose and extended laboratory test requirements as defined per TRL 3-4 evaluations, Appendix A, and per MIL-HDBK-510.

B. Tactical Generator Sets

Two evaluations were conducted to determine the impact of operating tactical generator sets on the SPK blends. There were no significant impacts to operability, performance or durability when

operating on the SPK blends as compared to operation on JP-8. Further discussion for each of these evaluations follows.

Side-by-Side Operation: In this evaluation three 10-kW tactical generator sets were operated at 50% capacity side-by-side for a total of 1000 hours each, some on SPK fuels and the other on JP-8. There were no discernible differences in performance between the generator sets during operation except that reduced emissions were evident when operating on SPK/JP-8 blend and SPK blending stock. This was an expected outcome as the SPK blending stock does not contain sulfur or aromatics which will translate to a reduction in exhaust emissions. There were no fuel leaks of any fuel-wetted components despite fuel switching during the test duration. There was no unusual wear of pump components based on visual inspection after post-test teardown of the engines.

Performance and Durability: The performance and durability evaluation operated a range of tactical generator sets, from small to large capacity (2-kW to 100-kW), that had a variety of fuel injection systems and high pressure fuel pumps on an SPK blend. As of the time of writing this report, the performance portion of the evaluation is only partially completed. An addendum to this report will be issued once this testing is completed. The expectation is that this evaluation will show no significant impacts to generator set performance when operating on the SPK blend. This expectation is supported by positive results from the many other evaluations conducted, including the performance of 10-kW tactical generator sets operated in the side-by-side evaluation. In the 1500 hour durability portion of the evaluation, there were no failures or issues attributable to the use of the SPK blend fuel.

C. Tactical and Combat Ground Vehicles

Five types of evaluations were conducted to determine the impact of operating ground vehicles with the SPK blends: (1) fuel injection system evaluations, (2) engine cetane window evaluations, (3) engine performance and durability evaluations, (4) a vehicle test track evaluation, and (5) vehicle demonstrations. There were some impacts to performance and durability that are attributable to variation in fuel properties. These impacts are similar for SPK blends and JP-8 taking into consideration the range of properties for SPK blends compared to JP-8 as previously discussed in Section V (subsection A, Fuels) of this report. Further discussion for each of these evaluations follows.

Fuel Injection Systems - Stanadyne Rotary Distributor Fuel Injection Pump: This evaluation found that the durability of this pump when operating on SPK blends was similar to when operating on petroleum JP-8, even at elevated temperature (170°F fuel inlet). This evaluation also showed that this pump is sensitive to fuel lubricity, just as other previous evaluations of this pump have found. The study highlighted the importance and effectiveness of the military-approved CI/LI in improving fuel lubricity, including at elevated fuel temperatures. The JP-8 specification requires all JP-8, including proposed drop-ins for JP-8 (e.g., SPK blends), contain CI/LI. The study also recommended that for continuous operations in elevated temperature environments, the maximum treatment rate of CI/LI, in accordance with MIL-PRF-25017, be utilized in all aviation kerosene fuel in order to protect rotary fuel injection pumps.

Fuel Injection Systems - HPCR Systems: This evaluation found that two of the three unique High Pressure Common Rail (HPCR) fuel injection systems tested performed well and also did not undergo significant component wear when operating on SPK blend or on JP-8, and also as compared to when operating on diesel fuel (ULSD). This is a positive result in that it appears, albeit based on this very limited testing, there may be some HPCR systems capable of performing well on military fuel (i.e., JP-8) and proposed drop-in fuels to replace JP-8 such as the SPK/JP-8 blends.

Specifically, this evaluation found the following in regards to the performance and durability of the three different HPCR systems tested. The Cummins XPI HPCR had good performance and durability when operated on SPK blend and petroleum JP-8, including operation at the highest test fuel temperature of 93°C. The Bosch HPCR system found in the 2011 Ford 6.7L engine, specifically the Bosch CP4.2, had similar performance and durability when operated on SPK blend and on JP-8, and also as compared to when operating on diesel fuel (ULSD). The Denso HPCR system found in the John Deere 4.5L Powertech Plus engine, specifically Denso Part Number HU294000-0564, was found to be sensitive to fuel viscosity, with failures at 4-5 hours of test time when fuel viscosity at test temperature (93°C) was 0.61 cSt or lower. The sensitivity of the Denso HPCR system to fuel viscosity and possibility for viscosities of less than 0.61 cSt at elevated temperatures (approaching 100°C) is irrespective of the source of jet fuel (i.e., petroleum JP-8, SPK blend or SPK blending stock).

Engines - Cetane Window: The two engines in this evaluation were the GEP 6.5L Turbo and the Caterpillar (CAT) C7. This evaluation found that there were clear trends for fuel property-related performance impacts in the two engines tested. Findings were that cetane number was just one of several key properties influencing engine performance; other key properties include, but are not limited to, fuel density, bulk modulus, carbon content, aromatics, distillation temperatures at 10% and 90% recovery points, and viscosity. A correlation study of various fuel properties and engine performance indicators was completed as part of this evaluation to more clearly identify specific property-performance impacts.

One outcome from this evaluation was the recommendation for a cetane number for ground vehicles between 40 and 60. One observation was that fuels with cetane numbers lower than 40 may be detrimental to some engines because of excessive heat release rates. The effects from this phenomenon, over time, could damage internal engine components. In addition, when engines and the environment are cold, engines are harder to start with low cetane number fuels and could possibly not start at all. The cetane number for SPK blends will tend to be better than for JP-8 as discussed in Section V (subsection A, Fuels) of this report.

Another observation was that fuels having very high cetane numbers (>60) can result in lower power output (peak power) for some engines with adaptive Electronic Control Modules (ECM). Lower power output with operation on high cetane number fuels was observed for the CAT C7 engine during some of the conditions tested (speed-load combinations). The evaluation concluded the reason this engine responds this way is because the ECM controls are modifying injection timing to control emissions of nitrous oxides (NOx). There is no requirement in any existing fuel specification that limits the cetane number to a maximum value. However, the cetane number of SPK blends is likely to always be less than 60 because even though the cetane

number of the SPK blending stock can be as high as 60, the cetane number of JP-8 is typically less than 50. The data presented in Table 17 shows that the cetane number of SPK blends falls between 47 and 54.

There were two other recommendations that resulted from the cetane window evaluation. One recommendation was that the volatility for fuels used in ground engines should have a distillation temperature gradient of greater than 50 for the temperature difference between the 90% and 10% recovery points. The diesel fuel specification, ASTM D975, contains a requirement for a minimum temperature at the 90% recovery point, but no requirement for a distillation temperature gradient. As shown in Table 17, the JP-8 specification does contain this requirement, specifically a temperature gradient of greater than 22 and 40 for the SPK blending stock and SPK blends, respectively. As the data shown in Table 19 indicates, the temperature gradient ($T_{90}-T_{10}$) for SPK blends falls between 75 and 86 which is well above that of 50 recommended in the cetane window evaluation report.

The final recommendation from the cetane window evaluation was that the isentropic bulk modulus of fuels for engines employing Pump-Line-Nozzle (PLN) type fuel injection systems (e.g., GEP engine) be greater than 180,000 psi (at 30°C, 0 psig). This evaluation found that fuel bulk modulus was the most significant fuel property affecting the peak power of the GEP engine, followed by fuel density. A well known fact established by many prior studies for the automotive industry is that for PLN injection systems, the delay between the pressure rise in the injection pump and the needle lift event increases with decreasing fuel bulk modulus. In effect, the fuel injection timing is retarded with decreasing fuel bulk modulus. (58) This means that for engines with PLN injection systems, fuels with lower bulk modulus values will inject fuel later in the combustion cycle than is optimal, resulting in lower engine efficiency (lower power output). As discussed previously in Section V (subsection A, Fuels), there is limited data available on the isentropic bulk modulus of current fuel (petroleum JP-8) to know whether there is a percentage of current JP-8 that may have a bulk modulus of less than 180,000 psi. From the previous discussion of the data presented in Table 22, the SPK blends can have a bulk modulus somewhat less (~172,000 psi) than the recommended value in the cetane window evaluation report. Also from the discussion in Section V, the densities for SPK blends will be no lower than the minimum required by the JP-8 specification, and in fact JP-8 batches procured in recent years have had densities close to this minimum. In any case, the Army's vehicles have engines that are designed to provide optimal performance using diesel fuel, and not petroleum JP-8. So, even if the Army were able to succeed in justifying a new requirement for a minimum bulk modulus in the JP-8 specification for SPK blends, this would not address the loss of performance from engines operating on petroleum JP-8 rather than diesel fuel. This topic is touched upon again in the discussion on the evaluation of the HMMWV test track performance later in this section (V, Discussion) of this report.

Engines - Performance and Durability: The performance portion of this evaluation found that the performance (e.g., power, torque, fuel consumption) of some engines is more sensitive to changes in fuel properties (e.g., density, volumetric energy content, etc.) than for other engines. The most important fuel properties with respect to engine performance were discussed previously in this section which showed that these properties for the SPK blends are very similar to those properties of petroleum JP-8. However, these properties may vary significantly

compared to the primary fuel (diesel) the engines were designed to use. The engine performance evaluation also found that performance changes can be even more pronounced for high temperature operation and at certain engine speed/load conditions. These results are not unexpected. Since some properties are temperature dependent, performance at elevated temperature can be impacted. The durability portion of this evaluation found that engines were able to complete full test endurance cycles with operation on the SPK blends. A summary of engine durability results from dynamometer testing is provided in Table 24. The performance portion of this evaluation found that engine performance can vary based on the properties of the fuel, and that the performance of the GEP 6.5LT engine is very dependent on some key properties of the fuel. A summary of engine power output results from dynamometer testing is provided in Table 25.

Table 24 - Summary of Engine Durability Results from Dynamometer Testing

Engine	Fuel (Protocol¹)	Results Summary – Engine Durability
GEP 6.5LT	SPK blend (1)	FT SPK blend: Engine completed 400-hr test with no fuel-related failures; no undue engine wear upon post-test tear down inspection. HEFA SPK blend: Inconclusive. Fuel injection pump failed during test, results not yet available as to cause of this failure. However, BOCLE data shows lubricity of HEFA SPK blend is similar to JP-8, so unlikely pump failure is fuel wear-related and similar results to be expected for HEFA SPK blend vice JP-8 at 400 hours.
Caterpillar C7	SPK blend (2)	Engine completed 400-hr test with no fuel-related failures; no undue engine wear upon post-test tear down inspection.
	SPK neat (4)	Engine completed 2×210-hr test designed to simulate 40,000 miles of proving ground operation. Oil degradation was not sufficient to halt test and component failures that did occur were not fuel- or lubricant-related. No significant engine wear or deposits upon post-test tear down inspection.
DDC 8V92TA	SPK blend (1)	Engine completed 400-hr test with no fuel-related failures; no undue engine wear upon post-test tear down inspection.
Cummins VTA-903T	SPK blend (2)	Engine completed 400-hr test with no fuel-related failures; no undue engine wear upon post-test tear down inspection.
Navistar MaxxForce 9.3D	SPK blend (2)	Engine completed 400-hr test with no fuel-related failures; no undue engine wear upon post-test tear down inspection.
Ford 6.7L Powerstroke	SPK blend (3), SPK neat (3)	Engine completed 210-hr test designed to simulate 20,000 miles of proving ground operation. Oil degradation was not sufficient to halt test. No component failures occurred. No significant engine wear or deposits upon post-test tear down inspection.

¹Test Protocols:

- 1 - 400-hr NATO cycle, ambient temperature
- 2 - 400-hr NATO cycle, elevated temperature
- 3 - 1×210-hr TWV cycle, elevated temperature
- 4 - 2×210-hr TWV cycle, elevated temperature

Table 25 – Summary of Engine Power Output Results from Dynamometer Testing

Engine	Fuel (Protocol ¹)	Results Summary – Engine Power Output
GEP 6.5LT	SPK blend (1)	This testing corroborates results from the Cetane Window Evaluation's correlation study which showed this engine's power output varies with changes in fuel properties. Power loss was evident with a change from operation on diesel fuel to either JP-8 or SPK blend, and also with change from operation at ambient temperature to elevated temperature. FT SPK blend: Less power was produced operating on FT SPK blend as compared to the specific JP-8 baseline fuel, as much as 6.3% less (0 hrs, Engine 2, at rated power speed). The density, energy density and cetane properties of these test fuels were similar. The FT SPK blend viscosity (at 40°C) of 1.3 mm²/s is slightly less than the 1.4 mm²/s for the JP-8, although it's well within the overall range for petroleum JP-8. This slightly lower viscosity can explain some power loss. The correlation study showed bulk modulus to be a significant factor affecting this engine's power output. As previously discussed in this report, there is limited bulk modulus data for petroleum JP-8. Without sufficient understanding of bulk modulus variation for JP-8, it's not possible to draw conclusions about the significance of bulk modulus variations and power output deltas between JP-8 and FT SPK blends. HEFA SPK blend: Similar trends were seen in this testing as the engine produced less power operating on HEFA SPK blend as compared to the specific JP-8 baseline fuel. The correlation study showed that density is also a significant factor affecting this engine's power output. The HEFA SPK blend density of 0.780 kg/L is significantly less than the 0.817 kg/L for the JP-8, although it's still well within the overall range for petroleum JP-8. The correlation study also showed that kinematic viscosity can affect this engine's power output, although less so than bulk modulus and density. The HEFA SPK blend viscosity of 1.3 mm²/s is somewhat less than the 1.5 mm²/s for the JP-8, although it's still well within the overall range for petroleum JP-8.
Caterpillar C7	SPK blend (2)	This testing also found that engine power output is impacted by changes in fuel properties, just as was also found in the Cetane Window Evaluation. Power loss was evident with a change from operation on diesel fuel to either JP-8 or SPK blend and also with change from operation at ambient temperature to elevated temperature.
	SPK neat (4)	In this testing, the engine's maximum power output, at rated power speed, ranked from high to low for operation on diesel fuel, JP-8, SPK blend and SPK neat. This ranking held for start and end of test (420 hours operation on SPK neat at elevated temperature). The power output at end of test, as compared to diesel fuel, was -1.8% for JP-8, -2.8% for SPK blend, and -3.5% for SPK neat. This trend was in line with fuel density (kg/L): diesel - 0.849; JP-8 - 0.791; SPK blend - 0.775, and SPK neat - 0.755.
DDC 8V92TA	SPK blend (1)	This testing found that property differences between the SPK blend and JP-8 baseline fuel had little impact on engine power output.
Cummins VTA-903T	SPK blend (2)	This testing found that this engine's power output is not very sensitive to changes in fuel properties.
Navistar MaxxForce 9.3D	SPK blend (2)	This testing found that this engine's power output is not very sensitive to changes in fuel properties.
Ford 6.7L Powerstroke	SPK blend (3), SPK neat (3)	This testing found that this engine's power output is not very sensitive to changes in fuel properties.

¹Test Protocols: see Table 24

Ground Vehicles - Test Track Performance (HMMWV): This evaluation found similar fuel economy results for operation of the HMMWV with the SPK blend tested as compared to the JP-8 tested. The evaluation did find some difference in vehicle acceleration results for operation with the SPK blend tested as compared to the specific batch of JP-8 tested; the results showed some degradation in the acceleration for the SPK blend. The ballasted HMMWV (to 10,300 lbs) had slower accelerations of -7.8% uphill and -17.7% downhill and the empty HMMWV had slower accelerations of -6.6% uphill and -14.0% downhill when operated on the SPK blend as compared to the JP-8 used in this testing. The SPK blend tested in comparison to the JP-8 tested had a higher cetane number (53 vs. 46) and higher viscosity at 40°C (1.2 cSt vs. 1.1 cSt), but a lower density (0.774 kg/L vs. 0.793 kg/L) and a slightly lower calculated volumetric energy density (121,450 Btu/gal vs. 123,510 Btu/gal). The slightly lower energy density alone does not entirely explain the performance degradation. The cetane window evaluation results discussed previously indicated that GEP engine (used in HMMWV) performance is sensitive to fuel density and bulk modulus, in addition to other factors such as cetane number. It may be that the lower fuel density of this particular SPK blend versus the JP-8 used in this evaluation, as well as other unknown differences (bulk modulus), could also contribute to the degradation in performance found in this evaluation. This is a prime example of where engines with the capability to readjust operating parameters, such as fuel injection timing or volume of fuel injected, based on variations in fuel properties could be beneficial for the military. Batch properties of JP-8 will differ, within the constraints imposed by requirements in the JP-8 specification, because of variations in crude oil sourcing and refinery configurations. The performance of engines with closed loop control would be re-optimized for the batch of fuel in use, whether that be JP-8 that was sourced from a refinery in Texas or JP-8 (SPK blend) sourced from a refinery in Qatar.¹¹ TARDEC sponsored research on this topic is documented in several papers, including the latter three cited here associated with the 2011, 2012, and 2013 NDIA Ground Vehicle Systems Engineering and Technology Symposium. (61, 62, 63, 64)

Ground Vehicles - TWV Pilot Field Demonstration: During this demonstration of SPK blend conducted at Fort Bliss, TX for a length of one year, a total of 47,000 miles was accumulated across a mix of light, medium, and heavy tactical wheeled vehicles that consumed a total of 9,500 gallons of SPK blend fuel. A similar mix of vehicles was operated on JP-8 as control vehicles during the demonstration period. There were a total of 28 test vehicles in the demonstration. Of these, a couple operated nearly 5100 miles on the SPK blend, many only a few hundred miles and the remainder somewhere in between. No issues arose with vehicle operation throughout the demonstration, and drivers and mechanics involved in the demonstration found no discernible differences between operations of the test vehicles versus the control vehicles.

Ground Vehicles - Demonstration at Camp Grayling: During this demonstration of SPK blend conducted at the Camp Grayling Joint Maneuver Training Center in Michigan, a total of

¹¹ The first cargo of synthetic jet fuel blend for export, containing 25% (by volume) of FT SPK manufactured at the Pearl Gas-to-Liquids (GTL) Plant in Qatar (jointly developed by Qatar Petroleum and Shell) was loaded at the Port of Ras Laffan on 11 June 2013 (<http://www.tasweeq.com.qa/EN/MediaCenter/EventsCalendar/Pages/Tasweeq-and-Pearl-GTL-witness-first-export-of-GTL-Jet-Fuel.aspx>).

10,000 gallons of SPK blend fuel was consumed by a wide variety of tactical ground equipment including various tactical ground vehicles, generators, light sets, construction equipment, environmental control units, and containerized kitchen trailer and laundry units. This occurred over an approximately two week period while Michigan Army National Guard Units operated this equipment during annual summer training exercises. Throughout the duration of this demonstration, no significant or unexpected issues arose with vehicles or other equipment that operated on the SPK blend.

D. Tactical Ground Support Equipment

Two evaluations were conducted to determine the impacts of operating petroleum and water systems (PAWS) equipment on the SPK blends. There were no significant impacts to operability, performance or durability when operating on the SPK blends found by one evaluation or expected for the second evaluation which has not finished. Further discussion for each of these evaluations follows.

PAWS Pilot Field Demonstration - Distribution and Handling Equipment: This evaluation found no issues with the performance of bulk fuel and water distribution and handling equipment when operating with the SPK blend. In addition, this evaluation found no issues with the durability of the two selected pump / engine assemblies (350 GPM and 600 GPM) after completion of the 400 hour test protocol.

PAWS Pilot Field Demonstration - AAFARS: At the time of writing this report, the evaluation of the AAFARS is not yet started, although set-up is complete and testing is about to begin. There is a high degree of confidence that this evaluation will show no impacts to the performance of any of the fuel-wetted components throughout the recirculation loop or AAFARS itself, or to the durability of the pump / engine assembly with operation on SPK blends. The basis for this expectation are the positive results from testing done with similar fluid handling components and pump / engine assemblies in the previous portion of the PAWS Pilot Field Demonstration – Distribution and Handling Equipment. An addendum to this report will be issued once this evaluation is completed.

VI. CONCLUSIONS & RECOMMENDATIONS

The results from the numerous completed evaluations completed that have been presented in this report provide ample evidence to support of the recommendation that the candidate SPK blends (FT, HEFA) be approved for use in DoD/Army tactical and combat ground vehicles and other tactical ground equipment. The SPK blends have been found to be drop-in replacements for conventional JP-8 fuel.

The implementation of SPK blends as an allowable ground fuel will be via a simple amendment to the JP-8 specification that removes the clause prohibiting their use as a ground fuel. The JP-8 specification already contains all the requirements for SPK blends. The Defense Logistics Agency (DLA) procures JP-8 fuel to meet these requirements. SPK blends, when procured, will be delivered to the user simply as JP-8.

Some fuel injection systems and/or engines are more sensitive to changes in certain fuel properties, e.g., density and bulk modulus. These properties can vary from one batch of JP-8 to another, although all within allowed limits per the JP-8 specification. To achieve optimal engine performance regardless of the source (batch) of JP-8, the Army should continue to research and develop technologies that allow closed loop control for military engines. Engines having this capability could perform better overall with JP-8, as well as with diesel fuel which is an allowed fuel per the Single Battlefield Fuel Policy in the case that jet fuel is not available or cost-prohibitive.

The Army should continue research on the bulk modulus of JP-8 fuels as well as approved and candidate drop-in replacements for JP-8. This research should focus on better understanding of the variation in this property amongst these fuels and its impact on engines and various subcomponents.

Finally, the qualification of future alternative fuels (other proposed drop-in fuels to replace JP-8) should follow a streamlined approach by drawing from the existing and extensive knowledge of the composition and properties of SPK blends (FT, HEFA) and the impacts of their use on military ground system performance and durability. This streamlined approach should significantly reduce the amount of TRL 5-7 testing needed based on the understanding developed in this work and on similarities in physiochemical properties of the future alternative fuel with those of SPK blends and JP-8.

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VIII. ACRONYMS

FT	Fischer-Tropsch
BTL	Biomass-to-Liquid
CTL	Coal-to-Liquid
CBTL	Coal-Biomass-to-Liquid
GTL	Gas-to-Liquid
HEFA	Hydroprocessed Esters and Fatty Acids
SPK	Synthetic Paraffinic Kerosene
FT SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
HEFA SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HRJ	Hydroprocessed Renewable Jet

APPENDICES

APPENDIX A

Qualification Roadmap

Qualification Roadmap

Evaluation	Pre-FY09	FY09	FY10	FY11	FY12	FY13
TRL 1 - 4¹						
Basic Fuel Properties and Composition	FT	HEFA				
Fuel Specification Properties	FT	HEFA				
Fit for Purpose Testing	FT	HEFA				
Extended Property Testing	FT	HEFA				
TRL 5						
Fuel System 1 (STANADYNE Rotary)	AmbT		Elev T			
Fuel System 2 (CUMMINS ISL-XPI HPCR)			Elev T			
Fuel System 3 (FORD POWERSTROKE-BOSCH HPCR)				Elev T		
Fuel System 4 (JOHN DEERE POWERTECH HPCR)				Elev T		
TRL 6						
					Engine Tests	
Engine 1 (GEP 6.5LT)	E1 ²	E3	E4	E3	E1	Performance & Emissions
Engine 2 (CATERPILLAR C7)	E2	E3	E4		E2	210-hr TWV Test Cycle
Engine 3 (DETROIT DIESEL 8V92TA)			E3		E3	400-hr NATO Test Cycle
Engine 4 (CUMMINS 903)			E3		E4	Cetane Window Evaluation
Engine 5 (CONTINENTAL 1790)				E3		
Engine 7 (INTERNATIONAL MAXXFORCE)				E3		
Engine 8 (FORD 6.7L)			E2 ³			
Tactical Gen Sets (10 kW)	G1					
TRL 7						
Tactical Gen Sets (2, 3, 10, 15, 30, and 100 kW)			G2		G3	
Test Track Performance (HMMWV)			Gen Set Tests			
Gr Vehicle & Equipment Demos		TWVs	G1	Performance & Operability	Gr Veh & Equip	
Petroleum and Water Systems Demos			G2	1500-hr Reliability		
			G3	Electrical Performance		

QUALIFICATION REPORT - SPK/JP-8 BLENDS (FT, HEFA)

¹ TRL 1-4 testing primarily conducted by aviation stakeholders² Non-Turbo engine variant³ Four fuels in testing matrix

APPENDIX B

Technology Readiness Levels for Fuel Qualification

TRL 1: BASIC PRINCIPLES OBSERVED AND REPORTED

1	TEST	
	<i>Basic Fuel Properties Observed and Reported</i>	MSDS (provided by supplier)
		Thermal Stability (Quartz Crystal Microbalance)
		Freeze Point (ASTM D5972)
		Distillation (ASTM D2887)
		Hydrocarbon Range (ASTM D6379 & D2425)
		Heat of Combustion (ASTM D4809)
		Density, API Gravity (ASTM D4052)
		Flash Point (ASTM D93)
		Aromatics (ASTM D1319)

TRL 2: TECHNOLOGY CONCEPT AND/OR APPLICATION FORMULATED

2	TEST	
Fuel Specification Properties (Table I)	Color, Saybolt (ASTM D156 or D6045)	
	Total Acid Number (ASTM D3242)	
	Aromatics (ASTM D1319 & D6379)	
	Sulfur (ASTM D2622)	
	Sulfur Mercaptan (ASTM D3227)	
	Distillation Temperature (ASTM D86)	
	Flash Point (ASTM D56, D93, or D3828)	
	Density (ASTM D1298 or D4052)	
	Freezing Point (ASTM D2386, D5972, D7153, or D7154)	
	Viscosity at -20°C (ASTM D445)	
	Net Heat of Combustion (ASTM D4809)	
	Hydrogen Content (ASTM D3343 or D3701)	
	Smoke Point (ASTM D1322)	
	Naphthalenes (ASTM D1840)	
	Calc. Cetane Index (ASTM D976 or D4737)	
	Copper Strip Corrosion (ASTM D130)	
	Existent Gum (ASTM D381)	
	Particulate Matter (ASTM D2276 or D5452)	
	Filtration Time (MIL-DTL-83133H, Appendix C)	
	Water Reaction Interface Rating (ASTM D1094)	
	Electrical Conductivity (ASTM D2624)	
	Std Test Method for Thermal Oxidation Stability of Aviation Turbine Fuels - JFTOT (ASTM D3241)	
	Gas Chromatography (Chemical Description) (ASTM D2887)	
	Literature Search on the fuel candidate	

TRL 3: ANALYTICAL & EXPERIMENTAL CRITICAL FUNCTION AND/OR CHARACTERISTIC PROOF-OF-CONCEPT

3	TEST
Fit for Purpose Properties	Lubricity Evaluation (ASTM D5001)
	Low Temperature Properties (Scanning Brookfield Viscosity)
	Polar Species (analyze as necessary to detect, quantify, and/or identify)
	Dissolved Metals (analyze as necessary to detect, quantify, and/or identify)
	Material Compatibility Evaluation - Micro-optical dilatometry and partition coefficient measurements; (1) 3 o-ring materials (nitrile, fluorosilicone and fluorocarbon) and 0- 2 more fuel system materials from Table I, ALTERNATIVE AND EXPERIMENTAL JET FUEL AND JET FUEL BLEND STOCK EVALUATION; (2) rest of Table I materials expected to have performance deviations (experimental fuel vs petro JP-8)
	Fuel System Icing Inhibitor (FSII) (ASTM D5006)
	Water Separation Index (ASTM D3948)
	Additive Compatibility (ASTM D4054)
	Autoignition Temperature (ASTM E659)
	Bulk Modulus (ASTM D6793)
	Dielectric Constant (ASTM D924)
	Derived Cetane Number (ASTM D6890) [add by Army-TARDEC]
	Flame Speed Test
	Flammability Limits (ASTM E681)
	Hot Surface Ignition (Federal Test Standard 791C Method 6053 or ISO 20823 Hot Surface Temperature)
	Specific Heat (as a Function of Temperature)
	Storage Stability (MIL-STD-3004)
	Surface Tension vs. Temperature (ASTM D971 or D1331)
	Thermal Conductivity vs. Temperature (ASTM D2717)
	Trace Elements (ASTM D7111)
	Vapor Pressure , True vs. Temperature (ASTM D5191 or D323)
	Viscosity vs. Temperature; Viscosity at 40°C [add by Army-TARDEC]
	Density vs. Temperature
	Water Solubility (ASTM D6304)
	ESOH Review

TRL 4: COMPONENT AND/OR BREADBOARD VALIDATION IN LABORATORY ENVIRONMENT

4	TEST	
	Extended Laboratory Fuel Property Testing	Analytical Comparison
		Ames Mutagenicity Test
		Dermal Irritation Test
		Acute Oral or Inhalation Test
		Fuel Thermal-Oxidative Stability (Estudios de Combustibles a Atlas Temperaturas (ECAT) and Extended Duration Thermal Stability Test (EDTeST))
		Cetane Number (ASTM D613) [add by Army-TARDEC]
		Minimum Spark Ignition Energy
		Ostwald Coefficient/Gas Solubility (ASTM D2779)
		Pour Point (ASTM D97)
		Thermal Expansion, Coefficient of
		Hot Surface Ignition
		Electrical Conductivity vs. Temperature
		Velocity of Sound
		Ignition Energy, Minimum
		Materials Compatibility (Short List of Materials)
		APU Low Temperature Fuel Nozzle Spray Test

TRL 5: COMPONENT AND/OR BREADBOARD VALIDATION IN A RELEVANT ENVIRONMENT

5	TEST	
	<i>Component Rig Testing</i>	Sector Test
		Pump Test (Rotary Distributor/Inline Injection, Common Rail/Unit Injectors) [add by Army-TARDEC]
		Hot Section Oxidation/Erosion
		Two Week Rangefinder with Genotoxicity
		Human Lymphocyte Genotoxicity

TRL 6: SYSTEM/SUBSYSTEM MODEL OR PROTOTYPE DEMO IN A RELEVANT ENVIRONMENT (GROUND OR SPACE)

6	TEST	
	<i>Small Engine Demonstration / Engine Testing</i>	Short Duration T-63 Test or Laboratory Combustor
		T-63 Demonstration (extended)
		Advanced Reduced Scale Fuel Simulator System-evaluation of fuel's coking tendency in large-scale test rig with actual airframe components
		APU Testing (short duration)
		Demonstration with Relevant Engine - Performance/Emissions (Williams or Honeywell engine)
		Tactical/Combat Vehicle Engine Dynamometer Testing [add by Army-TARDEC]
		Tactical Generator Set Testing (short duration) [add by Army-TARDEC]
		Toxicity Test (conduct a 90-day test with doses based on 2 week rangefinder study)

TRL 7: SYSTEM PROTOTYPE DEMONSTRATION IN A SPACE/**GROUND** ENVIRONMENT

7	TEST
7	Enthalpy vs. Temperature
	Fuel Handling and Storage Systems Analysis
	APU Testing
	APU Evaluation (JP-8/Biofuel 50/50 Blend and JP-8/SPK/Biofuel 50/25/25 Commingled)
	Afterburning Engine Altitude Test Cell Evaluation JP-8/Biofuel 50/50 Blend and JP-8/SPK/Biofuel 50/25/25 Commingled)
	On-Aircraft Evaluation (ground and flight - similar to B-52 evaluation; one aircraft for each fuel candidate, e.g., F-15, C-130J - different types, different OEMs)
	Tactical Wheeled Vehicle Evaluation (limited duration/scope, e.g., Pilot Field Demos, Test Track Performance) [add by Army-TARDEC]
	Tactical Generator Set Evaluation (limited duration/scope) [add by Army-TARDEC]
	Petroleum and Water Distribution System Evaluation (limited duration/scope) [add by Army-TARDEC]
	Industrial Hygiene (IH) Review – Bioenvironmental Engineering (BEE) (identify potential exposure hazards based on the toxicity evaluation, recommend interim personal protection (PPE) or engineering controls (IH controls) to prevent exposure to personnel)
	Health Hazard Assessment (HHA) (conduct using an exposure assessment and the toxicity data)
	Environmental Review (review ecotoxicity, fate and transport data and potential pathways of exposure)

TRL 8: ACTUAL SYSTEM COMPLETED AND "FLIGHT QUALIFIED" THROUGH TEST AND DEMONSTRATION (GROUND OR FLIGHT)

8	TEST
Validation/ Certification	Material Compatibility Long List
	Fuel System Component Evaluations (e.g., Fuel Gauging Systems)
	Support Equipment and Vehicles
	Infrastructure Assessment (sufficient to support pathfinder evaluation, e.g., Filtration Evaluation)
	Ground Fire Protection Assessment
	Survivability/Vulnerability Evaluation
	Fighter Aircraft Flight Evaluation (a challenging representative, e.g., F-22 with JP-8/Biofuel 50/50 Blend and JP-8/SPK/Biofuel 50/25/25 Commingled)
	High-Altitude Aircraft Flight Evaluation (e.g., Global Hawk with JP-8/Biofuel 50/50 Blend and JP-8/SPK/Biofuel 50/25/25 Commingled)
	Tactical/Combat Ground Vehicle Evaluations - Proving Ground [add by Army-TARDEC]
	Tactical Generator Set Evaluation - Proving Ground (Aberdeen) [add by Army-TARDEC]
	Force Projection Equipment Evaluation - Proving Ground (national training sites) [add by Army-TARDEC]
	All Others by Analysis/Similarity (using pathfinder and validation and certification analysis, test and demonstration data)
	Toxicity Testing (conduct additional studies recommended based on the results of the 90-day study and health hazard assessment)
	Exposure Assessment: The Health Hazard Assessment should be reviewed or revised using additional exposure assessment and toxicity data. This would result in verification or an update of exposure limits (standards) for safe use of the alternative fuel.
	Environmental (conduct additional studies that were recommended based on the results of Subset 1)

TRL 9: ACTUAL SYSTEM "FLIGHT/**GROUND** PROVEN" THROUGH SUCCESSFUL MISSION OPERATIONS

9	TEST	
	Field Service Evaluations	Fighter Aircraft Field Service Evaluation (a challenging representative, e.g., F-22 with JP-8/Biofuel 50/50 Blend only)
		High-Altitude Aircraft Field Service Evaluation (e.g., Global Hawk with JP-8/Biofuel 50/50 Blend only)
		Tactical/Combat Ground Vehicle and Equipment Field Service Evaluation (long duration/wide scope) [add by Army-TARDEC]

APPENDIX C

AAFARS and FSSP Components

UNCLASSIFIED

System	Component (Qty)	Sub-Component (Qty)
AAFARS (NSN 4930-01-495-0024)	Pump-Engine Module (1)	Engine Module (1)
		Fuel Transfer Pump (1)
	Liquid Fuel-Filter Separator (1)	--
	Auxiliary Pump Module (1)	Pump Assembly, Auxiliary (1)
	Nozzle Kit (1)	CCR Nozzle Assembly (1)
		D1 Nozzle Assembly (1)
		Fuel and Oil Servicing Nozzle (1)
		Nozzle Recirculation Manifold (1)
	Hose Kits (3)	2" Discharge Hose (50'-2, 12'-2)
		3" Discharge Hose (100'-1, 6'-1)
	Suction Hose Kit (1)	2" Hose (7'-6)
	Drum / Discharge Fitting Kits (2)	2" Camlock Adapter (2)
		Tee (2)
		Valve, Elbow Coupler (2)
		2" Cross (1)
		2" Wye (1)
		Elbow (1)
		Recirculation Manifold (1)
	Drum Adapter Kit (1)	Camlock Adapter (various sizes-8)
		Connector Adapter (2)
	Storage Module (1)	Air Intake Assembly (1)
		Inlet Manifold (1)
		Flexible Coupling (1)
	Fuel Drum 500 Gal (1)	--
	Ground Rod Kit (1)	Ground Rods (3)
	Pressure Control (1)	--
FSSP (NSN 4930-01-347-4793)	Suction Hose (1)	4" Suction Hose (10'-1)
	Gate Valve (1)	4 " Gate Valve (1)