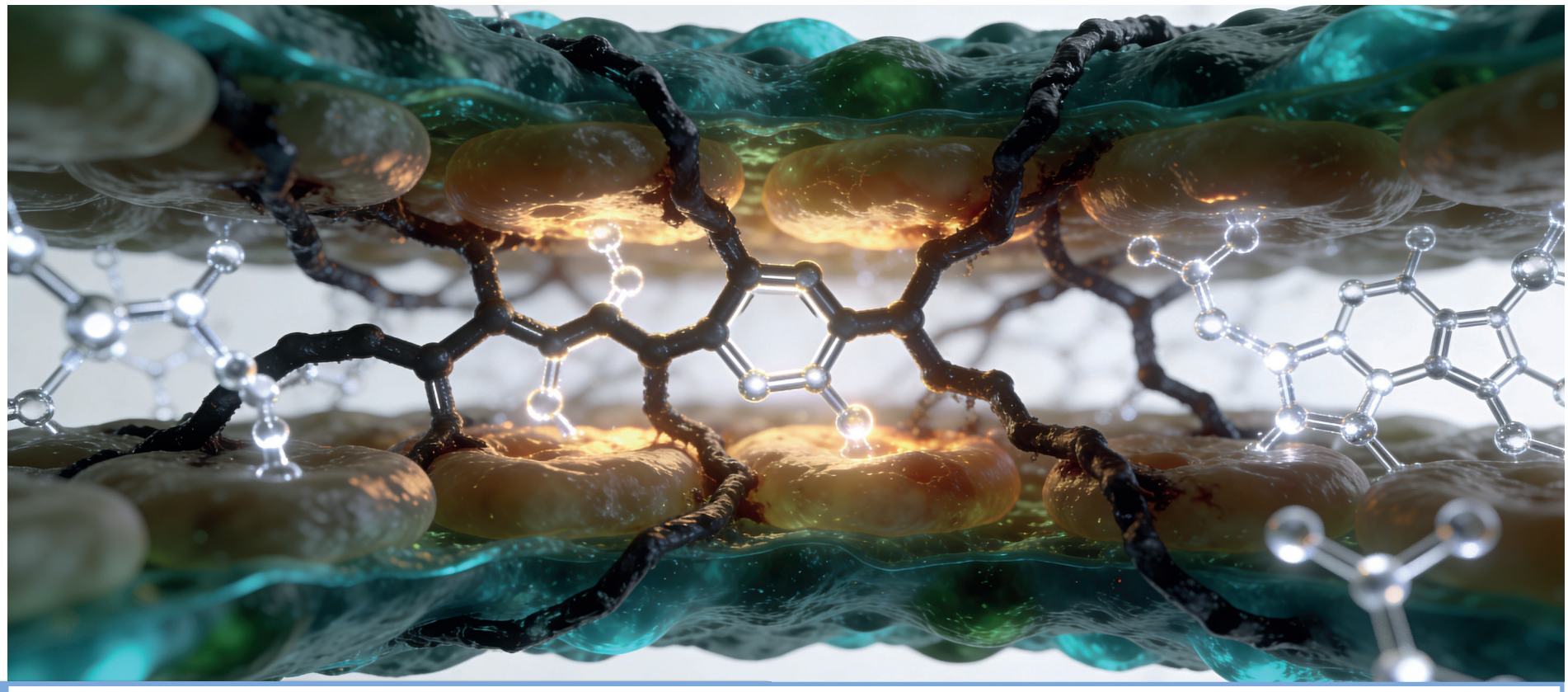

AROMATICS OUT, COMPATIBILITY IN? EVALUATING NITRILE SEAL PERFORMANCE WITH SUSTAINABLE AVIATION FUELS

Sustainable aviation fuel formulations based on synthetic paraffinic kerosene lack the aromatic hydrocarbons required to induce seal swell in nitrile butadiene rubber fuel system seals of older aircrafts. This structured literature review examines monocyclic and bicyclic cycloalkanes as non-aromatic swelling compounds. Measured volume swelling data from optical dilatometry and immersion testing indicate that 8% vol cycloalkane additions create insufficient swelling increases, but higher concentrations and blending can significantly influence volume swell. Production methods such as catalytic fast pyrolysis of pine biomass yielded products with 89-92 wt% cycloalkanes and liquid carbon recoveries of 91-92%, which promotes but does not prove the idea that these blends can replace aviation fuels, due to lack of ASTM D4054 qualification and physical elastomer compatibility testing.

Background and Scope

Air travel accounts for around 2.5% of all carbon dioxide emissions and 4% of all radiative forcing and is slated to continually increase due to global demand for fast transport methods (1). A significant amount of aviation emissions from airplanes burning aromatic fuels is created in the form of soot and particulate emissions, and poses significant health risks for the environment (1, 2). As we transition to cleaner aviation fuels to mitigate the climate crisis, we must focus on the issues caused by the chemical components of new fuels, and specifically their interaction with nitrile fuel seals. Current aromatic aviation fuels such as Jet-A and JP-5 induce swelling in nitrile elastomer seals, leading to proper fuel ratios reaching the engine and preventing catastrophic leaks, but also create soot and contrails when burned (2). The tradeoffs for aromatic fuels include their high energy per unit volume and ability to swell nitrile elastomer seals used to prevent leakages in fuel tanks (2). To achieve the goals of the International Air Transport Associations of going net zero by 2050, many synthetic non-aromatic sustainable aviation fuels (SAF) have been developed, specifically synthetic paraffinic kerosenes (3). Synthetic paraffinic kerosene (SPK) alternatives are unable to swell nitrile seals and currently require the blending of aromatic compounds to be commercially viable (2, 3). While most blends are able to satisfy the energy per unit mass requirements needed for flight, they do not account for the molecular interactions with the nitrile butadiene rubber (Buna-N) material that is commonly used in elastomer seals found in fuel tanks, leading to shrinkage of the seals, creating the risk of leakage or aeration of the fuel, causing disruptions in the engine (2). Because conventional aromatic hydrocarbons contribute heavily to soot emissions, monocyclic and bicyclic cycloalkanes have emerged as promising non-aromatic alternatives capable of swelling nitrile butadiene rubber (NBR) seals without generating excess soot. The goal of this paper is to discuss the multiple fuel blends and additions containing cycloalkane molecules, and their ability to induce nitrile seal swelling. Based on available research, cycloalkanes have been compared to synthetic and bio-derived aromatics in terms of solving swelling in SAF, and are among the strongest non-aromatic swelling agents due to their similar molecular structure (5, 9). The additives cis-decalin, trans-decalin, and cyclohexane are being compared in this paper (5, 6). Blend methods such as hydrotreating of lignocellulosic catalytic fast pyrolysis oils create fuels that naturally contain a majority of cyclohexanes and will also be reviewed (7).

SAF Qualification Framework

The American Society for Testing and Materials currently compares all jet fuels via standard specification ASTM D7566, which applies to any “drop-in” fuel (3). This specification requires any fuel to be compatible with any currently active airplane, including those without any modifications to the hardware, including nitrile fuel tank seals (3, 4). Current SAF blends exceed the energy requirements for fuels but swell at a much lower rate than standard jet fuels. Faulhaber et al. (5) tested the induced swelling on NBR O-rings by neat, unblended SPK, reporting a swelling value of 0.5%. The same experiment conducted using JP-5 fuel reported values of 22.5%, which serves as an example of a typical expected value healthy for fuel system seals(6). To artificially bridge this gap, the ASTM D7566 specification limits the amount of SAF synthetic blending components (3). This guideline is unlikely to be bypassed unless significant evidence is shown that SAF’s are able to swell nitrile seals to the levels of traditional fuels (3, 4). New SAF candidate blends must also undergo qualification under ASTM D4054 before incorporation into ASTM D7566 (4). The fuel has yet to undergo ASTM D4054, which would first test basic chemical properties and purpose based testing, and then rigorously test the fuel for combustor compatibility, engine endurance, and component level material (4).

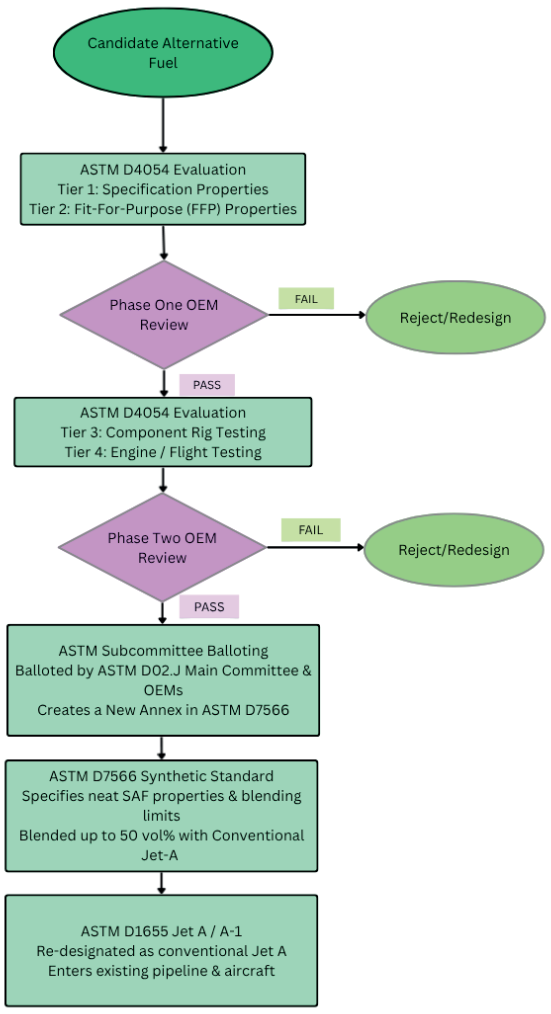

Figure 1: Flowchart of ASTM qualification and approval process for alternative aviation fuels. Fuels undergo property and combustor screening before gaining OEM approval and inclusion as an annex to ASTM D7566 for use under ASTM D1655.

Structured Literature Review

To evaluate the efficacy of non-aromatic swelling agents, a systematic review of technical literature was conducted. Databases including Google Scholar, ScienceDirect and ACS Publications were

canvassed by using search terms such as "cycloalkane sustainable aviation fuel", "sustainable aviation fuel swelling", "nitrile cycloalkane swelling" and other derivatives replacing broader terms for more specific ones. The inclusion criteria consists of experimental recording of volume or force of nitrile butadiene rubber exposed to hydrocarbon mixtures and synthetic jet fuels with thermodynamic parameters, compositional data, and standard physical properties. Airplane fuel tanks undergo rigorous conditions, notably large temperature ranges (-50℃ to 50℃) and mechanical compressive forces from aerodynamic load, hydrodynamic ram, and differential pressure (2). Due to the increased importance of these two conditions, it is required to choose studies focusing on swell properties of fuel blends in environments in which at least one of the two conditions is well replicated (5, 6). Specifically, studies were filtered by additive purity to confirm that each additive is at least 98% pure. Out of these studies, the ones chosen contained data for a wide variety of cycloalkanes, while studies for decalin and cyclohexanes were specifically chosen to cross reference data from initial sources (5, 6). Studies were excluded if they focused primarily on non nitrile elastomer seals and lacked comparable data to NBR. Fuel blend methods were chosen with the criterion that they contain extensive data on composition and environmental impact, filtered further to sort for methods resulting in cycloalkane fuels rich enough to swell nitrile seals (7). All papers with data pertaining to cycloalkane nitrile swelling were pulled from 2011 to 2025.

Seal Swelling Fundamentals

Nitrile swelling is dependent on the thermodynamic relationship between the fuel and the seal. In the aromatic case the simplified version of the Flory-Rehner theory (10) and the Hildebrand solubility parameters (11) state that maximum swelling occurs when the nitrile and fuel have the closest solubility parameters (10, 11). This is due to swelling equilibrium being directly related to the balance between elastic retractive forces of the polymer backbone and the free energy of mixing (10). Nitrile (Buna-N) rubber contains polar cyano groups, which allows for strong intermolecular dipole induced interactions due to the pi electron clouds in aromatic molecules (2, 10). Cycloalkanes on the other hand lack pi-electrons, meaning that their swelling mechanism is based upon optimal dispersion forces and having a high molar volume for optimal flooding (5, 6). At the lower 8% additive rate, trans-decalin created more swelling than cis-decalin due to its rigid, planar structure allowing efficient packing within the localized free volume of the polymer network (5). Notably, cis-decalin creates more swelling in nitrile seals compared to trans-decalin at high percentages, likely due to the fact that cis-decalin contains a less rigid structure, with a highly folded molecular geometry when compared to trans-decalin, creating a higher density and solubility parameters that more closely align with the Buna-N seal material, allowing for better penetration of the crosslinked polymer network in order to increase volume (6). Cyclohexane possibly has the ability to surpass both isomers of decalin due to its lower molar volume and steric hindrance, as it is a monocycloparaffin rather than a bicycloparaffin (5). Smaller molecular volume allows for the molecule to easily slide between the nitrile matrix while packing in a more efficient structure due to the greater flexibility of a single ring (5). It is important to note that aircraft fuel systems require controlled compatibility rather than maximum volume swell. Excessive swelling causes extreme plasticization, causing drastic tensile strength loss, reduction in hardness, and increased susceptibility to compression or shear tears (12). Swelling responses are also reactive to acrylonitrile content, as higher ACN content increases polarity, reducing swells in nonpolar fuels while increasing in polar aromatic compounds, requiring further testing with multiple formulations of nitrile seals (12).

Measured Swelling Studies

Optical dilatometry is commonly used in order to track volume swell via cross-sectional area measurements, which is done by using light and cameras in order to track the object's shadow (5). Faulhaber et al. (5) employed the dilatometry method with the use of heat chambers set to 37℃ to increase the speed at which the fuel diffused into the nitrile seal, reducing the test duration while maintaining realistic environmental parameters (5). These oven tests were cross referenced with tests conducted at 22℃ to confirm that the increased heat did not lead to significant change in the overall swelling differences (5). These trials were repeated seven and six times respectively to create a swell dataset with high efficacy (5). Luning Prak et al. (6) used a similar method, in which Buna-N rings were submerged in fuel mixtures for seven days and were constantly monitored using cameras to find the percent swell increase (6). Faulhaber et al. (5) show a contrast between base fuels and cycloalkane-doped blends (5). Percent swell is recorded as the fraction of volume increase when O-rings have been saturated in fuel doped with 8% by volume of additive, as compared to their default state (5).

Table 1: Experimental conditions and volume swell (%) of nitrile butadiene rubber (NBR). Faulhaber results are gathered from mixture of trial times dependant on temperature trial was conducted at (5-10 days at 37°C and 10-14 days at room temperature)

Study	Fuel / Fluid Matrix	Elastomer Substrate	Temperature (°C)	Duration	Measurement Method	Measured Volume Swell (%)
Faulhaber et al. (2023)	Neat SPK (Gevo C-1)	Formulated NBR O-rings (Parker 216)	37.15 / 22.0	Equilibrium (5–14 days)	Optical Dilatometry	~0.5%
Faulhaber et al. (2023)	SPK + 8 vol% Cis-Decalin	Formulated NBR O-rings (Parker 216)	37.15 / 22.0	Equilibrium (5–14 days)	Optical Dilatometry	~1.7%
Faulhaber et al. (2023)	SPK + 8 vol% Trans-Decalin	Formulated NBR O-rings (Parker 216)	37.15 / 22.0	Equilibrium (5–14 days)	Optical Dilatometry	~1.9%
Faulhaber et al. (2023)	SPK + 8 vol% Cyclohexane	Formulated NBR O-rings (Parker 216)	37.15 / 22.0	Equilibrium (5–14 days)	Optical Dilatometry	~2.0%
Luning Prak et al. (2025)	50 vol% ATJ-SPK + 50 vol% JP-5	AS Buna-N O-rings (AS3578-203)	21	7 days (168 h)	Dimensional Metrology (Optical)	~12.40%
Luning Prak et al. (2025)	10 vol% Cis-Decalin + 45 vol% JP-5 + 45 vol% ATJ-SPK	AS Buna-N O-rings (AS3578-203)	21	7 days (168 h)	Dimensional Metrology (Optical)	~16.0%

Direct experimentation shows a distinct gap in between synthetic paraffinic kerosene, cycloalkane-doped blends, and conventional aromatic fuels. Faulhaber et al. (5) used optical dilatometry to ascertain that the unblended SPK was only able to cause a marginal 0.5% swelling, which is an undesired result validating the original problem statement (5). The addition of 8% volume cyclohexane increased the swell to 2%, which is far below the swell range of typical jet fuel (5). Cis-decalin factors slightly below cyclohexane at 1.7% swell and trans-decalin reports at a higher value of 1.9% swell (5).

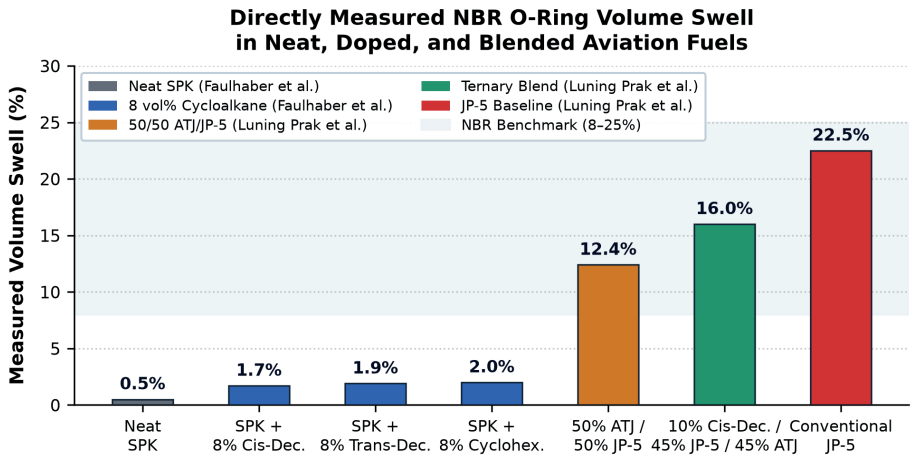

Figure 2: Equilibrium volume swell (%) of nitrile butadiene rubber (NBR) O-rings exposed to unblended synthetic paraffinic kerosene, SPK doped with 8 vol% cycloalkane additives, 50 ATJ-SPK, 10% cis-decalin in 45/45 JP-5/ATJ and conventional JP-5 jet fuel.

In multi-component blend evaluations, Luning Prak et al. (6) measured dimensional swelling of AS Buna-N O-rings over a period of 168 hours at 21C, finding that JP-5 produced 22.5% swelling, while a 50/50 vol% blend of ATJ-SPK created 12.4% swelling. An increase of 10% vol cis-decalin to 45% ATJ-SPK/ 45% JP-5 mixture increased the value to 16%, implying that cycloalkane additives have lower swelling effects than aromatic dopants.

Table 2: Chemical composition, carbon recovery yields, and structure property relationship model predictions for cycloalkane rich aviation fuel blends

Study	Candidate Pathway / Model	Reported Composition / Yield	Measured Property	Inferred Seal Compatibility
Kosir et al. (8)	Machine Learning (QSPR Model)	Various hydrocarbon mixtures	Volume Swell Prediction (<12.4% error)	High predictive accuracy for drop-in fuel screening
Chen et al. (7)	Lignocellulosic Catalytic Fast Pyrolysis	89-92 wt% Cycloalkanes; <0.01 wt% Oxygen	Carbon Recovery (91-92%)	High cycloalkane fraction suggests potential swelling equivalence, but physical seal swell was not directly measured
Liu et al. (9)	Solvent Swelling Property Analysis	Decalin/ Hydrocarbon Solvents	O-ring Swelling Property (OSP)	Identifies ~60 vol% cycloalkane content as a target range to match aromatic swelling

Cycloalkane Rich Production Pathways

Rather than use pre-made additives, blend methods look to generate cycloalkanes through fuel processes, using renewable feedstocks such as wood, farming scraps, algae, and industrial waste (7). One such method includes the hydrotreating of lignocellulosic catalytic fast pyrolysis oils carried out in Chen (7). In the test environment, pine needle biomass was rapidly heated in a chamber containing either an acidic zeolite catalysts or Pt/TiO2 catalysts to depolymerize the cellulose, hemicellulose, and lignin into a deoxygenated bio-oil (7). This oil was then refined in a continuous trickle bed reactor using a presulfided NiMo/Al2O3 catalyst, at 125 bar and a temperature range averaging 385℃. The high energy environment stimulates the hydrodeoxygenation and aromatic ring saturation to create cycloalkane rich fuels (7).

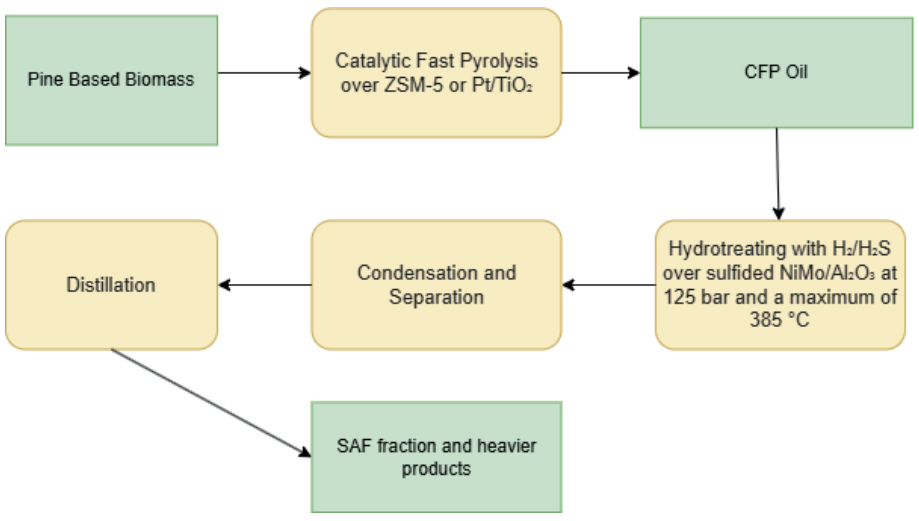

Figure 3:Author-created simplified block-flow diagram based on Chen et al.; shown for process context and not as a validated process simulation .

The method of catalytic fast pyrolysis explored in Chen (7) proved to have both strong catalytic recovery and a strong yield of cycloalkanes. This fuel also surpasses the cycloalkane volume lower limit of 60% outlined by Liu (2013) (9) for a separate decalin system, indicating that it is possible for its swell value to suffice requirements, although more testing is needed. A strong 91-92% of the biogenic carbon present in the bio-oil was converted to a liquid phase hydrocarbon, a strong yield that supports green chemistry through a high carbon recovery (7). Furthermore, cycloalkanes made up 89-92% of the SAF by weight, which is a significant portion compared to the additive based methods tested (7). The hydrodeoxygenation of the fuel was also near total, resulting in an oxygen content fraction lower than the analytical detection limit of <0.01 wt% (7). The method of catalytic fast pyrolysis is a robust method that is able to handle pine based biomass due to the extreme conditions and the nature of the sulfided NiMo catalysts (7). This ensures that the normally unyielding phenolic intermediates fully deoxygenate and hydrogenate, resulting in a fuel rich in cycloalkanes, predicted to be able to meet required physical specifications (3), such as lower heating value, freeze point, and viscosity due to composition (7). It can also be observed that methods to refine biomass, such as pine, corn husks, and algae can successfully yield fuels that contain non-aromatic swelling compounds in high quantities, showing much promise for future testing on its swelling capabilities. (7, 9).

Fuel Property Tradeoffs

There are consistent tradeoffs between SPK's and traditional jet fuels that must also be considered before establishing the use of SPK's in commercial settings (2, 3). While SPK's are noted to have a large energy to mass ratio, their low density results in a lower energy to volume ratio compared to common aviation fuels, restricting the range of airplanes using it due to the lower total energy that can be stored (2). Bicyclic compounds have higher freezing points and kinematic viscosities that are higher than the expected operating conditions of airplanes, which creates danger in the use of higher quantity blends of these additives (2, 6). Lack of proper fuel refining can compromise the fuel's thermal stability, leading to degradation in the fuel (2). Alternatively, a poor fuel blend encourages coking, shortening the time needed before repair to constantly clear the solid debris accumulating in valves and channels (2).

Limitations and Research Gaps

Despite the abundance of cycloalkanes in the derived fuels, material compatibility for drop in fuels or additives can not be confirmed without multiple direct tests of fuels made using this method (5, 7). Swelling tests for non-aromatic fuels are a common starting point for many research institutions due to the importance of adhering to legacy guidelines (2, 3). Due to the recent nature of the research information, many other tests are required to confidently claim the success of cycloalkanes in SPK (5, 6). Long term aging and mechanical degradation tests evaluate the degradation of polymers, plasticizer extraction, and compression under continuous exposure for long periods of time to test fuel stability (12). Wet and dry thermal cycling for the various models of nitrile seals would confirm the presence of swelling hysteresis, cracking, or rapid shrinking during dry phases, which impact the long term effectiveness of the seal itself. The greatest requirement for the use of SPK blends in airplane systems is reliable swelling data for any variation of fuel created, such as the catalytic fast pyrolysis oils created in Chen (7).

Conclusion

To phase out fossil fuels and replace them with synthetic alternatives, it is important that we fully understand the fuel nitrile interactions to ensure total safety (2, 3). Conventional aromatic fuels create soot and other harmful particles when burned, but are able to reliably swell nitrile seals (1, 2). Based on available data, it would appear that cycloalkanes show promise in producing swell necessary for fuel system seals when used alongside aromatics, although further testing is required to concur with this analysis (5, 6). SAF engineered with monocyclic and bicyclic cycloalkanes in particular shows great promise in matching the swelling requirements for that of Buna-N seals in fuel tanks, although further testing is still required to make a conclusive statement (5, 6). While current data suggests that non-aromatic compounds such as decalin and cyclohexane in large enough quantities create swelling that may be comparable to standard aviation fuels like JP-5 and Jet-A (2, 6), further research would need to support the safe burning of these experimental SPK blends in order for the ASTM to consider changing their specification (3) to allow for greener fuels. By tailoring the chemical composition of SAF to utilize these non-aromatic structures, the aviation industry can move towards its goals of reducing its carbon footprint to contribute to a healthier biosphere.

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