<u>Title: HEFA Feedstock Cost Reduction</u>

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Gap/Problem statement:

Sustainably produced natural oil feedstocks are not currently available at sufficient volume or price to meet demands for production of HEFA fuels. Technological improvements are needed in the areas of plant biology and breeding, agronomy practices for novel feedstocks, improved fermentation approaches and strains for heterotrophic oil production, and a better understanding of the effects on broader markets of using waste animal fats. By bringing the production costs of natural oils down, the economics to scale up production of these feedstocks, and therefore of HEFA fuels will become more favorable. This white paper outlines some of the key technology challenges facing the affordable production of HEFA feedstocks, and indicates some high-priority areas where research efforts could produce needed results.

Background:

With HEFA fuels approved for commercial use, the technical hurdles of producing a fit-for-purpose aviation biofuel from natural lipids and oils (free fatty acids, and fatty acid esters) have been addressed. This production route takes a high-energy feedstock (natural oils are the most energy dense storage molecules used widely throughout all biological life), and with relatively low exogenous energy requirements, upgrades it into hydrocarbon jet fuel. However, as the lipid starting material is high-energy, generally it is relatively expensive to produce. Food-grade commodity oils such as soybean, palm, sunflower, or canola all currently trade at prices higher than the fuel that could be made out of them, reflecting both their production costs in combination with their value for nutrition. However, the aviation industry is striving to develop non-food sources for biofuels, and apart from a few niche circumstances, these novel feedstocks are even more expensive to produce and purchase than the food oils mentioned above. There are four broad classes of these feedstocks, which are discussed below:

Plant oils: Many plants produce seeds and nuts which can be crushed to yield an oil that, after application of a standard set of pre-processing steps from the food oil industry, is entirely suitable for conversion to HEFA. The most promising candidates for aviation's purposes are inedible oils such as those produced by annual row crops (e.g. camelina or pennycress) or perennial shrubs or trees (e.g. castor, jatropha, or pongamia).

Heterotrophic microbial oils: Some yeasts, fungi, and certain algae are capable of fermenting sugars into lipids. These organisms are grown the in the dark in steel tanks, and receive an input of organic molecules that provide carbon and energy which they take-up, and convert into lipids. The accumulated biomass is harvested and dewatered, before the lipids are extracted by various means, pre-processed as above, and then are ready to convert to HEFA.

Photosynthetic microbial oils: Microalgae and certain engineered cyanobacteria have the capability to produce extremely high yields of oil on a given land area. These are grown under natural sunlight in water or an aqueous environment, fixing carbon dioxide into biomass by photosynthesis. A portion of the biomass produced will be lipid which can then be extracted through the same series of steps outlined above for heterotrophic organisms.

Waste oils: The production of certain food commodities yields by-product or waste streams that may be suitable as a feedstock for HEFA production. In fact the majority of HEFA-fuelled commercial flights to date have been sourced from waste animal fat and used cooking oil feedstocks. Additionally non-food grade lipid streams are generated in the processing of food oils.

Current Status:

Plant oils: Established agricultural commodity crops such as soybean and canola have gone through decades of development in both traditional breeding and new advanced genetics as well as continual agronomic improvements. However, inedible plant oils generally are sourced from relatively new, non-'domesticated' plant crops that do not have this history of development. Therefore these crops have considerable potential for both increased yields, and reduced input and farming costs. Additionally, the new biofuel feedstock crops are generally targeted for production on marginal lands with low irrigation requirements, so as to not complete with food production on high-value arable land and with valuable fresh water supplies. Such marginal growing conditions are not likely to produce high yields of biomass.

Heterotrophic microbial oils: Considerable effort has gone into the development of microbes which can ferment organic substrates into lipid-containing biomass. Single cell yeasts and heterotrophic algae can achieve this transformation. Commercial production of lipid-based nutraceutical products and cosmetics from this route is already established, although production costs are currently too high to allow fuel production competitively. Two major challenges need to be solved to bring production costs down. Firstly, inexpensive sustainable sources of organic carbon and energy need to be available. For most approaches, simple sugars such as glucose, sucrose or fructose will be the best input, however other lower cost sources are available, such as glycerol that is a by-product of biodiesel production. The ability to metabolize crude (ligno)cellulosic hydrolysates is also a target. Secondly, the microbes and their growth systems need to be optimized to increase yields and reduce operation costs.

Photosynthetic microbial oils: Algae as a biofuel feedstock has received a great amount of attention due to the potential for algae to convert industrial, agricultural and municipal waste streams into high value natural oils. Numerous combinations and permutations of the various approaches to each part of the technology chain have been trialed by research and commercial entities. Significantly scaled demonstration production facilities are currently being constructed. Yet, despite all of the considerable resources devoted to developing algae technology, algal oil remains prohibitively expensive.

Waste oils: Rendered animal fat from meat production is a mature, stable and relatively low-cost supply of HEFA feedstock. Additionally, from a sustainability perspective, the carbon LCA on animal fats is very good due to the standard ISO 14000 approach to 'zero-rating' the carbon load of a waste product. Whether that LCA calculation will hold in the future as demand grows and animal fats are perceived to transition from a waste to a by-product is a question that needs to be addressed.

Used cooking oil faces no such uncertainty as to its LCA impact, as it is truly an 'end-of-life' waste product. However, unlike rendered animal fat, supplies of used cooking oil are widely and unevenly distributed, and the major challenge to commercialization is the difficulty collecting enough oil together cost effectively to support a commercial refinery.

Generally, these waste oils also face challenges in terms of their chemistry, with high free fatty acid levels, and lowered oxidative stability. The former can lead to a requirement for more costly steel in transportation and processing equipment. The latter can reduce yield efficiency

General oil quality issues: The HEFA process is a catalytic conversion which may be sensitive to oil quality. Some oils can present a very high yield and low cost but may not be suitable for HEFA conversion. These "alternative oils" can present radically different compositions and consequently not be easily treated (low transformation yield) or need some high cost pretreatment step (for example, removal of metallic impurities). Moreover, the chemical composition of the oil is a key consideration. Carbon chain length will have an influence on the final product yield, and the relative yields of diesel and jet fuel, and consequently the final production economics.

Solvability and Approaches

Plant oils: Annual row crops have relatively short breeding lifecycles, suitable for progress through traditional crossing and selection, while marker-assisted breeding , mutagenesis and more advanced directed genetic modifications should be able to be accomplished, established and implemented on reasonable timelines.

Longer lived perennial trees and shrubs face greater challenges to develop the high-yielding cultivars within reasonable timeframe. Not only are generation times longer for these plants, but their lifetime in production may run into decades, meaning that producers will be cautious in establishing sub-optimal cultivars. Despite these challenges the methods mentioned above still apply for perennials.

The most obvious target trait for improvement in plant oil crops is the yield of oil per unit area. However improvements in that trait must also be balanced against and combined with targeted improvements in pest resistance, drought tolerance, and fertilizer input requirements. Some crops may have specific research targets. For instance, castor bean is a plant with many desirable characteristics as a biofuel feedstock. It is high yielding and has great drought tolerance. Yet it produces an extremely potent neurotoxin, ricin, which precludes it from practical commercialization. Breeding or targeted genetic knock-out to remove ricin from the castor bean would facilitate its commercial implementation.

One other significant opportunity for R+D to reduce the production cost of plant oils is in developing technologies for increasing the value of the non-oil meal or crop residue.

That such improvements in plant traits are possible is demonstrated soundly by the history of food crop agriculture. The tools, lessons and expertise accrued over decades of research in that field are equally applicable to the new crops under discussion here.

In terms of agronomy, the practices that are required to successfully and efficiently raise these crops, much of that work happens in large scale field trials and once the plants are actually growing in the farming or plantation setting. Advanced identification of potential insect and weed pests and the development of control measures for such would assist in smooth, uninterrupted scale-up.

Heterotrophic microbial oils: The single greatest cost-improvement available for HEFA from fermentation is cheaper sugars. This is certainly in large part a technological challenge, although it is one that has received billions of dollars of R+D investment over the past decades and is discussed is greater detail and with more authority elsewhere (http://www.annualreviews.org/doi/full/10.1146/annurev-chembioeng-061010-114205). Development of microbes which are able to utilize less processed sugars (i.e. partial hydrolysates, mixes of C5 and C6 sugars) would definitely bring a cost advantage.

Presuming a sustainable, inexpensive source of carbon and energy is available; there is still a need for technological improvement in fermentation approaches. Oxygen transfer and mixing are key factors which control rates and yields of oil production, and are also large cost drivers given the mechanical energy required to achieve both in dense fermentation broths.

Photosynthetic microbial oils: The numerous technological challenges and opportunities for R+D to bring down the cost of algal oil are well documented elsewhere, most notably and comprehensively by the US Dept of Energy in their "National Algal Biofuel Technology Roadmap" (http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf). There is little to be gained by repeating here the recommendations within that report, suffice it to say that research aimed towards bringing down the production costs of algal-derived oils should have a significant long-term impact on HEFA prices.

Waste oils: Clarity on the carbon LCA burden of 'waste' animal fats is necessary, if not for bringing costs down, at least for verifying/maintaining the sustainability credentials of this type of biofuel as it grows in scale.

The primary technological challenge with waste oils is ensuring that low-quality, acidic and degraded oils meet the requirements of the downstream processing into HEFA fuels. Methods for recovery of various waste-streams from the traditional vegetable oil refining industry, and the separation of viable HEFA-inputs need to be developed, validated, and improved to reduce costs. Of particular value would be methods to recover the fatty acid backbone from glycol- and phospholipids which are waste products know as 'gums' produced in the processing of food-grade vegetable oils.

Benefits to industry as a whole

While other processing technologies are still being developed or face commercial challenges, HEFA fuels are being produced at commercial scale in a number of large biorefineries around the world. The challenge with these fuels is in sourcing low-cost oils and lipid feedstocks. Increasing supplies of less expensive feedstocks will increase supplies of price-competitive aviation fuel.