Microfine hydrocarbon:

a novel approach to upgrading coal into higher-value oil products

A unit of energy from oil is regularly valued at six times the value of a unit produced by coal. The arbitrage has been valued at approximately $20 trillion over 15 years.¹ Today only a few hundred thousand barrels a day of oil products are produced from coal, substantially less than 0.5% of global oil production. Attempts to upgrade coal to higher-value fuel products on a commercially viable scale have been made, but without success until now.

Arq Ltd. (“Arq”) has developed a novel process for manufacturing a microfine² hydrocarbon³ from coal and coal discard. This breakthrough overcomes the challenges of the past, with capital and operational expenditures that are orders of magnitude lower than any comparable process. It enables more profitable uses of coal to be realized.

The feedstock for the process comes from the discard material produced at coal mines. The coal industry produces over one billion tons of coal waste every year: the energy equivalent of discarding over five million barrels of oil daily. Global slurry lakes contain equivalent energy to approximately 70% of Saudi Arabia’s petroleum reserves. The Arq process captures lost energy from above-the-ground hydrocarbons while cleaning up a major environmental liability.

Microfine hydrocarbon extends the finite reserves of crude oil, and its refined distillate products, and has the potential to become one of the world’s lowest-cost fuels. Arq estimates the combined market for coal and oil products to be worth $2 trillion a year.

¹ CAPP coal futures reported on a $/short ton basis for 12,500 btu/lb thermal coal. 1 short ton of coal = 25 million BTU; WTI prices reported on $/bbl basis. 1 bbl of crude = 5.8 million BTU; the annual arbitrage in price is multiplied by the volume of coal consumed each year
² ‘Microfine’ refers to particles not exceeding 10 microns in diameter
³ Microfine hydrocarbon is a hydrocarbonaceous material, mainly carbon and hydrogen but containing some oxygen
Microfine hydrocarbon

Microfine hydrocarbon is a purified, high caloric-value, solid energy source derived from coal fines. With particles not exceeding 10 microns in diameter (vast majority less than 5 microns), containing less than 2% moisture, and with ash content below 1% m, microfine hydrocarbon is a suitable blending feedstock for a range of fuel oil products.
**Historical context**

Coal fines are small particles of coal generated from larger lumps during the mining and preparation process. While coal fines offer an economical and plentiful supply of hydrocarbons, they are generally considered a waste product. The mining industry traditionally favors a lump product. Not only is it difficult to liberate coal from mineral matter at the size fraction of coal fines, but their nature renders them difficult to market and transport.

Methods for adding coal fines slurries to oil products have been attempted in the past. However, in its natural state, coal fines waste typically contains high levels (often more than 50%) of ash-forming contaminants that would render it unsuitable for being blended directly with oil products. The amount of water present in coal fines (c. 35%) is also undesirable for use in oil products. Furthermore, coal-water emulsions require modifications to regular engine infrastructures and have poor inherent energy. Suitable coal fines can be manufactured by crushing and grinding seam coal with inherently low mineral matter content (e.g. less than 5%) however, this quite substantially limits the types of coal that can be utilized.

Alternative methods of converting coal directly into liquid hydrocarbon products have been explored, but largely proved uneconomical and environmentally damaging. These have mainly involved solvent extraction of coal at temperatures above 400°C under pressure in the presence of hydrogen or a hydrogen donor solvent to chemically change the structure of the hydrocarbons extracted from coal.

Sasol, a world leader in technology for converting coal to liquid fuels via synthesis gas, has withdrawn from new investments in the process. It has reported that new technologies for converting coal to liquids have proved economically unviable in commodity markets, while converting coal to liquids generates low returns and unacceptably high carbon dioxide emissions.

Today, only in countries where there is strong government support, such as China, are coal-to-liquid technologies still being pursued. This has led to several pilot-scale developments and at least one full-scale operating plant using the Shenhua process at Ejin Horo Banner, Ordos, Inner Mongolia. Exploitation of this process, however, involves a multi-billion capital investment and high associated running costs.
The Arq approach

Arq’s approach is unique within the energy industry. While previous attempts to upgrade coal have taken the source material as a starting point, Arq began by determining the requirements to make a commercially viable product. Microfine hydrocarbon has been engineered to be fit for purpose for the market.

Microfine hydrocarbon is not designed as a direct substitute for liquid fuels. Many of the units within coal’s polymeric structure have similar aromatic shape and size, and similar functional groups to those found in fuel oil. Based on this observation, the Arq team hypothesized that a microfine, coal-derived, solid hydrocarbonaceous material would be a suitable feedstock for blending directly into traditional fuel oils, without chemical modification.

Arq identified two challenges. Firstly, to create a hydrocarbonaceous material that approximates the combustion performance of fuel oil, any ash-forming mineral impurities must be almost completely removed. Secondly, the physical nature of the resulting material must assume the rheology of a liquid oil product.

Arq subsequently developed a microfine hydrocarbon with particles not exceeding 10 microns in diameter (vast majority less than 5 microns), less than 2% moisture and ash content below 1‰. Microfine hydrocarbon meets requirements for direct blending into liquid fuel oils without changing the blended product’s burning characteristics, without needing any change to engine infrastructure, and while maintaining dispersion stability.

Microfine hydrocarbon is a novel source of energy that reduces the cost per unit mass of the blended fuel oil. It will help close the gap between the value of a unit of energy produced from oil with that of a unit of energy produced from coal, and offers the potential to produce one of the world’s lowest-cost fuels. It delivers significant efficiency improvements for oil distributors and industrial and utility customers throughout the value chain, including logistical, financial, environmental and other benefits.
Reclamation

Coal fines are generally discarded as refuse close to mine sites, forming large waste heaps or slurry lakes that require careful future management in order to avoid environmental contamination. In extreme cases, this represents a threat to human life, as demonstrated by the 1966 Aberfan disaster in South Wales, the 1985 Val di Stava disaster in Italy, the 2015 Fundão disaster in Brazil and various other international incidents.

Coal discard, containing coal fines, is recovered efficiently and safely from slurry lakes, or sourced directly from coal mine underflow of mining partners.

The Arq process therefore has the added advantage of helping to remove a major environmental liability.

Micro-sizing

To enable the liberation of hydrocarbonaceous matter from mineral matter, the sizing process creates a micro-particle system through a series of advanced milling techniques. This results in particles not exceeding 10 microns in diameter (vast majority less than 5 microns).

Particle size reduction is achieved by ball milling, high shear grinding or a combination thereof.

Reducing particle size also helps maintain even dispersion of the solid in liquid fuel oil. Tests are under way to prove microfine hydrocarbon is fine enough not to be stripped out by engines, filters or marine centrifuges.
Micro-separation

Micro-separation removes most mineral impurities, resulting in an ash content of less than 1%.

Micro-separation is achieved via Arq’s proprietary froth flotation technique, a process for selectively separating hydrophobic from hydrophilic materials. This technology has traditionally been used to separate microfine particles in precious metal mining industries, but improvements to the technology have allowed Arq to apply the technique to microfine coal particles for the first time.

The removal of contaminants prior to combustion ensures microfine hydrocarbon approximates the oil with which it is blended. Being up to 99% pure, it also reduces the sulfur emissions of the blended oil product.

De-watering

De-watering dries the wet slurry, creating a microfine hydrocarbon containing less than 2% moisture.

Ultra-efficient mechanical de-watering to a wet cake and thermal drying to a powder is achieved via an innovative rapid evaporation system, leveraging recent technological advancements in the food processing industry. Arq is able to achieve the removal of water from the wet slurry with perfectly even dispersion into fuel oil — a novel advantage.

Dispersion is achieved by high shear mixing, ultrasonic mixing, or a combination of these.

The removal of water prior to combustion helps minimize gross specific energy (GSE) loss, resulting in greater fuel efficiency.

Product finishing

The microfine hydrocarbon is conditioned to create Arq Fuels™, a blend component for liquid fuel oil, such as marine fuel oils, residual fuel oil, bunker fuels and heavy fuel oil.

An alternative finishing process, “pelletizing”, produces a solid hydrocarbonaceous pellet for mixing with coal fuels.
Suitability for commercial application

A key commercial application of microfine hydrocarbon is for blending directly into Residual Fuel Oils (RFOs). RFOs, with calorific value in the range 38-43 MJ/kg, are used as the source of energy for thermal power stations, large industrial plants and engines, notably marine engines.

Arq Fuels™ are a more economical blending feedstock in two distinct markets, namely:

- Stationary combustion equipment, such as power plant, large industrial and commercial boilers (Arq Fuel Oil™)
- Marine engines and boilers (Arq Marine™)

The total volume of these markets is estimated at 400 million tons per year (roughly 200 million tons each). Arq Fuels™ meet the relevant technical requirements and conditions to enter these markets, with respect to relevant RFO specification and fitness for purpose of microfine hydrocarbon blends.

Tests prove that microfine hydrocarbon dispersed in RFOs can:

- Be stable enough to survive storage and transfer via the fuel supply system to large-scale stationary combustion equipment
- Meet the relevant specifications developed for both stationary and marine RFOs.

Arq’s microfine hydrocarbon has been tested by internationally accredited independent testing companies, including the foremost of these, SGS. Significant technical data has been collated and published, and can also be found in patent filings due to be published in 2018. What follows are the resulting conclusions drawn by Dr John F. Unsworth, former Technology Manager, Fuel Strategy & Alternative Fuels at Shell Global Solutions, now an independent consultant.

---

Dispersion stability

Dispersion of Microfine Hydrocarbon in RFO

The dispersion stability of microfine hydrocarbon in RFOs has been demonstrated at various storage temperatures and transfer conditions necessary for stationary combustion and marine applications.

Satisfactory dispersion stability has been determined for a range of storage times; temperatures rising to 120°C; microfine hydrocarbon concentrations in RFO ranging from 10%m to 30%m; and microfine hydrocarbon samples from 90% particle size below 4 microns to 90% particle size below 12 microns.

Tests have been conducted on microfine hydrocarbon prepared from different types of coal, such as high-volatile bituminous coals, and coals of Permian and carboniferous ages. Tests were also conducted using several RFOs selected from different refinery sources.

Test blends were shear mixed at high speed over different time intervals, then left to stand at 80°C for times up to seven days. The same concentration of solid was found in the top, middle and bottom samples, indicating uniform coal particle concentration.

Integrity of particle size distribution during storage

Integrity of particle size for blends of microfine hydrocarbon with RFOs has been demonstrated at the various storage temperature conditions and transfer conditions necessary for stationary combustion and marine applications.

Particle size distribution (PSD) was measured at ambient temperatures using a specially-developed dilution method to measure coal PSD in opaque, viscous liquids. PSD data for different layers confirmed the uniformity of microfine hydrocarbon dispersion.

Dispersion samples tested above at 80°C were then cooled to ambient temperature and stored for periods ranging from several months to over a year. Subsequent PSD measurements were compared directly with the PSD for the wet coal filter-cake from which the dried coal in the RFO-coal dispersion was derived, and shown to be almost identical.
Meeting international specifications

Stationary and marine RFOs are specified to protect sophisticated burner and boiler equipment, as well as limit boiler emissions.

For stationary uses, different specifications apply for the range of technologies and these vary according to the region or country of use, e.g. UK BS 2010 and ASTM 396. For marine use, international (ISO) regulations are applied. (See Appendix 1, Table 1 for stationary RFO specifications; Table 2 for marine RFO specifications).

RFO specifications for stationary combustion are less comprehensive than those for marine use. The test programs undertaken by Arq with respect to Arq Fuels™ are guided by and consistent with these specifications.

RFO specifications cover 17 parameters in all. These can be grouped as:

- Bulk physical properties: viscosity, density
- Chemical properties: sulfur content, total acid number
- Contaminants: ash content, water content, total sediment content, hydrogen sulfide (H₂S)
- Characteristic temperatures: flash point, pour point
- Trace elements: vanadium, sodium, aluminum and silicon, calcium, zinc, phosphorus
- Combustion

In addition, trading contracts between customer and supplier also specify required gross specific energy (GSE, caloric value) of RFOs.
Bulk physical properties: viscosity

RFO viscosity is increased by the addition of microfine hydrocarbon and by decreasing particle size. Particle size has a greater impact on viscosity than concentration.

The blending of 10% microfine hydrocarbon with RFO typically increases viscosity by one grade. Microfine hydrocarbon blends follow the same type of exponential relationship between viscosity and temperature as for the RFO alone, meaning viscosity at various temperatures can be readily predicted. If necessary, viscosity can be controlled by blending with a less viscous RFO solvent, such as light cycle oil.

Bulk physical properties: density

Fuel density is increased by the addition of microfine hydrocarbon and by decreasing particle size. Concentration has a greater impact on density than particle size.

Blending 10% microfine hydrocarbon with RFO typically increases density by one grade. If necessary, density can be controlled by blending with a less dense RFO solvent, such as light cycle oil.

Chemical properties: sulfur content

Currently, RFOs are traded at sulfur contents up to 3.5%m. From 2020, new regulations will demand a reduction in sulfur level to 0.5%m. Meeting these new requirements will have a significant impact on refinery configuration and operations, and hence cost.

The sulfur content of microfine hydrocarbon is typically in the range of 0.4%m to 0.6%. Its low sulfur content offers oil distributors a low-cost option to meet customer needs and regulations.

Chemical properties: total acid number (TAN)

Arq has shown from tests on two bituminous coals of different particle sizes that TAN can be reduced by addition of microfine hydrocarbon. Equally, TAN deterioration was not shown to occur with the addition of microfine hydrocarbon.

Contaminants: ash content

The ash content of microfine hydrocarbon is below 1%m (an order of magnitude purer than commercially-produced coals).

At an ash content of 1%m or less, microfine hydrocarbon can be added in proportions up to 15%m to the heavy RFO grades. If the ash content of microfine hydrocarbon is as low as 0.5%m (as is possible), then blends of 20%m to 30%m can be achieved.
**Contaminants: water content**
The targeted specification of microfine hydrocarbon is 1%-2% water. The proportion of microfine hydrocarbon that remains within specification varies from less than 15% to 50% respectively.

These maximum blends assume negligible water content present in the original RFOs to ensure compliance with international specifications and to minimize GSE loss when blending the product with marine and stationary RFOs.

**Contaminants: total sediment content**
The total sediment test has been determined not relevant when blending microfine hydrocarbon with stationary and marine RFOs. This conclusion is based on tests which prove stable dispersion of microfine hydrocarbon during distribution and storage.

Asphaltenes, a molecular substance found in crude oil which are prone to sedimentation, are not a component of coal. Test work is underway to establish whether microfine hydrocarbon actually stabilizes asphaltenes present in RFOs.

**Contaminants: hydrogen sulfide**
Residual sulfur in microfine hydrocarbon is non-volatile at ambient temperatures. Furthermore, the sulfur content of the Arq product is unusually low at 0.5%, and most is organically bound, meaning H₂S risk is low, lower than the risk from RFO itself.

**Characteristic temperatures: flash point**
In a range of coals of different rank, origin and particle sizes, the flash point of RFO is improved significantly when blended with microfine hydrocarbon. Tests show that a 5% of the Arq product increased the RFO flash point by more than 10°C. Further additions (10% and 15% blends) increased the point by an additional 5-10°C respectively.

This ability to manipulate the flash point of the blended fuel oil may be used to bring the blend back into specification if the non-blended fuel oil falls outside. There is currently no other product on the market that achieves this.
**Characteristic temperatures: pour point (PP)**

Addition of 10-15% microfine hydrocarbon results in an increased pour point (PP) of 6-12°C. Tests on a range of coals of different rank, origin and particle size show that PP increase for blends is greater for coals with the lowest particle size. These results are consistent with higher viscosity increases observed for lower coal particle sizes at the same coal concentration.

Typically, there is sufficient headroom between the PP of commercial RFOs and the marine RFO specification limit of 30°C to accommodate a PP increase of 10°C. Pour point can be controlled by blending with a less viscous RFO solvent, such as light cycle oil.

**Trace elements: vanadium and sodium**

Coal, unlike oil, contains little or no vanadium. Addition of microfine hydrocarbon typically reduces the vanadium content of the resultant RFOs. Sodium in RFO typically ranges from 3-7 ppm in the form of chloride salt. Microfine hydrocarbon has higher sodium content (of the order of 50-100 ppm), but is present as clay, bound within aluminosilicate structure. Sodium, in this clay form, is less available to bond during combustion with vanadium pentoxide than in conventional RFOs. Magnesium, a vanadium deposit inhibitor, is also present within microfine hydrocarbon at a level of 200-500 ppm.

The increased sodium content does not exceed the RFO specification. Vanadium and sodium limits are only specified for marine RFOs. Sodium limits are set at 100 ppm for most grades, i.e. a similar order of magnitude as the sodium level in microfine hydrocarbon.

A test program is underway with a marine single-cylinder bench engine to validate the effects of microfine hydrocarbon on vanadium- and sodium-derived deposits.

**Trace elements: aluminum and silicon**

On an empirical (rather than impact) basis, typical Al and Si values for 5%, 10% and 15% blends are approximately 150-200 mg/kg; 300-400 mg/kg; and 450-600 mg/kg respectively.

Coal-derived Al and Si, mainly in the form of clays, is less abrasive than catalytic Al and Si, meaning any wear characteristics for coal Al and Si are significantly lower. Arq finds that Al and Si are unsuitable indicators for machine wear arising from catalytic breakdown.

The Arq program of marine engine testing planned for 2018 will provide the direct evidence needed to alleviate
concerns relating to coal Al and Si abrasion of fuel pumps, injectors and cylinder liners in a single-cylinder bench marine engine.

**Trace elements: calcium, zinc and phosphorus**

Typical calcium, zinc and phosphorus values for a 10% microfine hydrocarbon blend is approximately 15 mg/kg (15ppm), <1 mg/kg (1ppm) and 1 mg/kg (1ppm) respectively, based on data for US bituminous coals.

On this basis, a microfine hydrocarbon blend would equal the calcium specification only at blends of 20%, and phosphorus at blends of 15%. It should be stressed that calcium itself is not a problem in fuel, and is used only to indicate the presence of used lubricating oil (ULO) in marine RFO.

**Combustion**

Arq testing on a low-volatile bituminous coal shows that microfine hydrocarbon increases carbon residue (CR) roughly in line with the fixed carbon content of the coal. The estimated CR increase is 6.4% for every additional 10% of microfine hydrocarbon. This limits the blend maximum to 25% in the best case, and 11% in the worst case.

Using standard laboratory methods, with a range of microfine hydrocarbon blends, Arq has determined ignition and combustion performance for compression-ignition engines. The results show clearly that blends at 15%m can perform well in normal large, low- and medium-speed, marine diesel engines.

**Gross specific energy**

A 10% microfine hydrocarbon blend has 1.5% lower gross specific energy (GSE, calorific value) than that of the base RFO; in the case of a 15% microfine hydrocarbon blend, calorific value is found to be 3% lower.

Although addition of microfine hydrocarbon to RFO reduces calorific value, the product remains a significantly higher-value option for use in stationary burners and boilers, and marine engines designed for RFO with minimal or no adaptation.
CONCLUSION

Arq has achieved a breakthrough in coal processing by creating a microfine hydrocarbonaceous product with particles not exceeding 10 microns in diameter, less than 2% moisture, and ash content below 1%m. This breakthrough enables more profitable uses of coal to be realized, and represents a novel approach to upgrading coal into higher-value oil products.

Arq test data demonstrates that microfine hydrocarbon blends can be prepared at scale and remain stable throughout the storage and transfer of RFOs in the stationary and marine markets. RFO blends containing up to 30%m microfine hydrocarbon are achievable for marine or stationary fuel grades.

The volume of the stationary and marine markets for Arq Fuel Oil™ and Arq Marine™ are sizeable at the global level. Unlike most new or unconventional fuels being launched into international markets, Arq’s own market entry does not require changes to the supply chain or to engines, boilers and associated equipment. It delivers significant efficiency improvements for oil distributors, industrial users and utility customers throughout the value chain.

As part of a dynamic pipeline of innovation, Arq is currently working with specialist partners to explore possible applications of microfine hydrocarbon for blending into crude oil. Testing to date has indicated potential for microfine hydrocarbon to maximize profitability for oil refineries. Development is ongoing.

The Arq process for producing microfine hydrocarbon requires capital and operational expenditures that are orders of magnitude lower than any comparable process, and lower than the equivalent production of oil. Beyond upgrading oil products, the Arq process can also be used to manufacture a pelletized product for mixing with traditional coal fuels. Uses include combining with metallurgical coals to enhance product performance in steel-making processes, and with thermal coals to increase efficiency and reduce emissions for energy utilities companies.

Arq is prepared for large-scale production. As well as the several sites Arq owns and controls, it has an ongoing program to identify new sites and supply-side partnerships that will most benefit from its technology. These include international partnership agreements with some of the world's leading coal companies. They also include independent sites, whose acquisition will help secure microfine hydrocarbon for the future. Expansion plans are already underway in the US, Australia, Europe, China, Russia, South Africa and India.
## APPENDIX 1 — INTERNATIONAL STANDARDS

### Table 1. US and UK RFO specifications for stationary combustion fuels

<table>
<thead>
<tr>
<th></th>
<th>UK BS 2010 RFO burner fuels</th>
<th>ASTM 396 heavy fuel oil grades</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>Viscosity @ 40°C mm²/s</td>
<td>min</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>-</td>
</tr>
<tr>
<td>Viscosity @ 100°C mm²/s</td>
<td>min</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>8.20</td>
</tr>
<tr>
<td>Density @ 15°C kg/m³</td>
<td>min</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>-</td>
</tr>
<tr>
<td>Ash content %m max</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Sulfur %m max</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carbon residue %m max</td>
<td>15.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Total sediment %m max</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Water %m max</td>
<td>0.5</td>
<td>0.75</td>
</tr>
<tr>
<td>Water &amp; sediment %m max</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flash point °C min</td>
<td>66</td>
<td>38</td>
</tr>
<tr>
<td>Pour point °C min</td>
<td>-6</td>
<td>-6</td>
</tr>
<tr>
<td>Acid number mg/K OH/g max</td>
<td>zero</td>
<td>-</td>
</tr>
</tbody>
</table>
Stationary RFO specifications are less detailed than marine ones. Some grade specifications are quite simple, e.g. ASTM No.6, which sets limits for just three parameters: viscosity, water and sediment, and flash point. Thus, amongst the stationary combustion grades, the following specification parameters are included in:

- All grades: viscosity and flash point
- Most grades: ash content, sulfur, total sediment, water content, or water and sediment (combined)
- Some grades: carbon residue and acid number
- One grade only: minimum density and pour point.

Marine RFO specifications are more comprehensive than stationary RFO ones with all grades setting limits for nine of the above parameters, i.e. all bar minimum density and (combined) water and sediment, plus maximum density, vanadium, sodium, aluminum and silicon (combined), H₂S and calcium, zinc and phosphorus contents.