Future aviation fuels

Work Package C3: Interactions Between Mitigation Measures and the Atmosphere

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Climate services for a net zero resilient world

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CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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In the short and medium-term sustainable aviation fuel (SAF) is the most straightforward technological pathway to reduce the climate impacts of aviation. SAF is already commercially available and can be blended into Jet A-1 for use with existing aircraft. SAF can be made via many different chemical engineering processes and from a range of feedstocks, including some waste products and biocrops.

A feature of all SAF is that the fuel is predominantly paraffinic and does not contain sulphur or substantial aromatic content. It is the absence of sulfur and aromatics that leads to notable air quality benefits compared to kerosene. Elimination of sulphur reduces new particle formation and particle number. Lower amounts of aromatic compounds reduce the formation of radical fragments in the exhaust gases that lead to soot and black carbon. Combustion of SAF still however generates nitrogen oxides (NO_x) emissions, as does kerosene. The amount of NO_x released by SAF-fuelled engines is largely unchanged since emissions are dependent on the temperature of combustion rather than the formulation of the fuel itself.

Hydrogen-fuelled jet aircraft have a long R&D history, and the principles of NO_x formation in exhaust as an unwanted by-product are well understood. The use of hydrogen does however bring clear benefits in terms of reductions in emissions of particulate matter (PM) and some other gases, but a wide range of NO_x emissions can result depending on operating conditions. Very low NO_x emission hydrogen turbines have been demonstrated, but there is some trade-off between lower NO_x and energy efficiency. Here the key issue is not technological feasibility to reduce this NO_x dis-benefit but the extent to which this is prioritised in policy and regulation. Along with NO_x, hydrogen jet engines lead to the emission of water vapour in exhaust, a notable effect in the upper atmosphere where it has climatic impacts. There remains considerable uncertainty regarding the overall climate effects of water vapour from hydrogen aviation combustion.

2. Combustion of future fuels for aviation

2.1 Introduction

Aviation is widely acknowledged to be one of the most difficult transport sectors to decarbonise, since the basic physics of flying requires the use of stable fuels with high energy density. As well as releasing CO_2, aviation is currently a source of health-relevant air pollution, significant around airports and immediately downwind regions, although currently modest in terms of contribution to total national emissions. Aircraft engines emit a range of non-CO_2 pollutants of relevance to air quality including particulate matter, nitrogen oxides, sulphur dioxide and non-methane hydrocarbons. Whilst aviation emissions have reduced with more modern engine technologies, sectoral emissions have remained broadly constant in some locations due to growth in aircraft movements (see National Atmospheric Emission Inventory).

At present, the overwhelming majority of commercial aviation uses kerosene fuel that meets the Jet A or Jet A-1 specification. This defines properties such as combustion heat, flash point, freezing point, viscosity, sulphur content and density. Small light aircraft use fuel of slightly different specification such as Avgas 100/130, Avgas 100LL or UL91/94. All these fuels are based on fossil hydrocarbons and are a distillation cut of aliphatic and aromatic compounds in the carbon number range 8-16. Aviation fuels also contain trace amounts of nitrogen and sulphur. The nitrogen and sulphur content of fuels is defined as part of the technical specifications and, whilst low in absolute terms, has substantial impacts on air pollution emissions, notably fine particle formation and on combustion performance. A range of synthetic additives are added at part-per-million levels to aviation fuels to reduce icing, as antioxidants, corrosion inhibitors, biocides, and lubricity improvers.

Decarbonisation of aviation and the exchange of fossil fuels for net zero carbon alternatives is unlikely to follow a single technology pathway. There are likely to be some elements of short-haul aviation that may be fully electrified using battery energy storage. For these the air quality and wider climate benefits are very significant since the combustion system is completely removed. However, many pathways towards net zero aviation involve the retention of gas turbine systems burning alternative fuels, either hydrocarbon-based or liquefied hydrogen. Retention of combustion within the aviation sector clearly has implications for air quality, although these are variable depending on the fuel. Reviewing the impacts of combustion of alternative fuels is the main focus of this chapter. In the longer term it is possible that fuel cell technologies may also play a role, with hydrogen fuelling, and this would also deliver aviation with no direct air quality or other atmospheric emissions (e.g. water vapour). The report does not consider the air quality impacts of the supply chain for alternative fuels, for example from feedstocks, manufacture or wider impacts arising from land-use change to produce biofuels. These are potentially significant and any disbenefits need to be captured in the lifecycle analysis of alternative fuels.

The peer reviewed literature as it relates to air quality effects of alternative aviation fuels is limited. In many cases assumptions on air quality impacts have to be drawn from basic knowledge of the underlying combustion processes rather than from direct field trials of particular engines or appliances.

2.2 Combustion of liquid hydrocarbons

A wide range of different processes have been developed that can convert a range of feedstock materials into liquid hydrocarbon fuels, with a lifecycle that can be delivered close to carbon neutral, or that use waste products that if not used for this application would have delivered no further value. The international nature of aviation means that common standards for fuel properties are in place and so irrespective of the chemical production method and feedstock, alternative liquid fuels currently aim to recreate the chemical properties of fossil-derived kerosene as closely as possible. The rationale is primarily operational – a synthetically derived fuel with close to identical properties of kerosene can be directly substituted for those hydrocarbons, either in blends or as a pure fuel. Liquid hydrocarbon fuels of this kind have been widely badged as Sustainable Aviation Fuels (or more commonly SAF). Whilst many SAF are derived from biomass feedstocks, and so are also technically biofuels, there are routes to the production of SAF that use other feedstocks, and so biofuels and SAF are not directly interchangeable terms.

Table 1 provides some examples of production methods and feedstocks for fuels which can currently be blended with Jet A-1 fuel.

Table 1 Potential methods of production of synthetic aviation fuels, the originating feedstocks used, and currently recommended maximum blends from ICAO.

Production method	Feedstocks	Blend % with kerosene
Fischer-Tropsch Paraffinic Kerosene / or with aromatics	Multiple including biomass, wood, straw, some municipal waste streams diverted from landfill	50
Ester and Fatty Acid Hydroprocessing	Oil bearing biomass crops such as algae, jatropha, camelina, carinata	50
Power to liquid (Fisher Tropsch)	CO_2 to CO conversion then reaction with H_2 derived from electrolysis	50
Sugars to Isoparaffins Hydroprocessing	Microbial conversion of sugars derived from biomass crops.	10
Alcohol to paraffinic kerosene	Agricultural waste, grasses, forestry waste, straws	50

The chemical content of SAF generated by the processes in Table 1 is somewhat variable, but in general terms is a mix of long-chain aliphatic compounds with very low aromatic content. Since the fuels are derived from biological organic material precursors, or from CO and H_2 in power to liquid fuels, these precursors have very low heteroatom content, generally present only because of the ingress of impurities in the production process. When combusted these fuels burn with slightly different characteristics to fossil-derived fuels.

2.3 Impact of aromatic content on particle emissions

Aromatic compounds have a complex role in aviation fuel applications and resulting impacts. They are often reported as playing a role in engine lubrication, although it is notable that whilst a maximum volume percentage of aromatics (and naphthelenes) forms part of formal Jet A and Jet A-1 fuel specifications, there is no minimum content requirement. Aromatic contributions to lubricity performance arise primarily from oxygen, nitrogen and sulphur-functionalised aromatic additives, rather than simple fossil-derived aromatic hydrocarbons. An argument against the use of 100% SAF has been that it is typically low in aromatic hydrocarbons and would therefore not meet requirements for lubricity. This is not necessarily consistent with advice from aviation fuel producers however:

From Chevron, Aviation Fuels: Technical Review "…*low sulfur or aromatics levels in jet fuel are not, per se, signs of inadequate lubricity*."

Many studies have reported that the aromatic content of aviation fuel is a significant factor in controlling the formation of non-volatile particulate matter (nvPM) and black carbon (BC) in the engine exhaust. Brem et al. 2015 found significant increases (~60%) in emissions of BC and nvPM, for relatively modest increases of aromatic content in fuel (increasing from 18% to 24%). The nature of the aromatic compounds also had an impact, naphthalenes increased emissions even if total aromatic content was kept constant.

The direct impacts of using low aromatic SAF were reported by Scripp et al. 2019, who found that compared to standard kerosene, a hydroprocessed fuel with high aromatic content increased PM emissions whilst an aromatic-free alcohol to jet fuel led to ~70% lower PM emissions. The differences were, as with Brem et al., ascribed to the aromatic cleavage during combustion forming radicals prone to sooting.

A study of 15 different aviation fuels used in a single DC-8 aircraft (Moore et al. 2015) also identified that aromatic content was a key determinant of overall PM emissions, and that low aromatic and low sulfur jet fuels from biobased or Fischer-Tropsch production would lead to lower emissions. A similar result was found during a test on 16 different fuels, albeit it in a laboratory setting by Zheng et al. 2018, whose work also identified that the presence of cycloparaffins as well as aromatic compounds led in general to higher PM emissions. Cycloparaffins are also typically much lower in SAF fuels than kerosene. Other supporting evidence is reported in older literature based largely on laboratory scale studies for example in Beyersdorf et al. 2014, Cain et al 2013, and Timko et al 2010.

Implications: There is a modest sized body of literature that indicates that in real-world settings gas turbine emissions of non-volatile PM and BC are lower with synthetic fuels (e.g. manufactured from feedstock materials other than fossil crude oils) than present day fossil-fuel based Jet A-1 fuels. Most tests in the peer reviewed literature have been conducted on Fischer-Tropsch fuels. The benefits of this reduction if these fuels are used in aviation would be two-fold. They would result in a reduction in non-volatile PM emissions during taxi and take-off phases and likely be of benefit to local air quality around airports. There would also be a sustained reduction in BC emissions during flight which could reduce positive radiative impacts from this pollutant during cruise phases. It is during cruise that most BC emissions / climate impacts are thought to occur (Wilkerson et al. 2010). The effects on the total number of particles (Particle Number PN), as distinct from particle mass, are less clear, however there is emerging evidence that the lowering of sulphur content when SAF is blended reduces PN as well as PM mass[1].

SAF can lead to environmental benefits in terms of reduced greenhouse gas impacts when the lifecycle of production and use of fuel are considered together, the engines themselves still lead to emissions of CO_2 at point of use. SAF fuelled aviation is not emissions-free from a particle pollution perspective at the point the fuel is used, but its wider uptake could lead to lower emissions than at present (if volume of activity was kept constant). This may have effects in both climate and air quality domains; upper troposphere emissions of PM can enhance the formation of contrails and more persistent cirrus clouds, which are climate warming. PM released in the lower atmosphere impacts on health and ecosystems. A growth in overall volume of aviation and air travel, and hence higher overall emissions would potentially erode some of the climate and air quality benefits arising from lower PM per unit fuel used.

2.4 Gaseous pollutants from SAF combustion

There is only limited literature on the impacts of synthetic fuels on other gaseous pollutants when used in aviation applications. Cain et al. provides one of the most useful datasets, which indicates that emissions of carbon monoxide (CO) from a Fischer-Tropsch fuel of around 98% isoparaffinic composition were around 10-20% lower than an existing comparator fossil aviation fuel. Emissions of certain volatile organic compounds (VOCs) were also lower, for example toluene. This largely reflected initial fuel composition rather than any intrinsic improved combustion performance. Indeed, emissions of acetaldehyde from the synthetic fuels were proportionally higher than fossil jet fuel hydrocarbon emissions. Overall, unburned VOCs could be found in exhaust irrespective of fuel type,

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[1] See in progress projects such as https://aviation-pm.eu and https://aviatorproject.eu.

with the implication that the use of SAF may alter the speciation of VOCs that are emitted, but not fundamentally change the total mass of reactive carbon emitted. Evaporative losses of fuel during fuel storage and handling are typically low for aviation and would not be expected to change substantially with the use of SAF, since fuel vapour pressure properties would be very similar to fossil kerosene. Hence the overall VOC air quality effects are likely to be broadly neutral in nature.

Emissions of NO_x from different fuels including SAF and Jet A-1 are reported in Cain et al. and in Khandelwal et al. 2019. The overall effect of changing the fuel type does not appear to materially impact the NO_x emissions released.

To quote from Cain et al. "*The total NO_x (NO and NO_2) emissions were minimally affected during operation with the various fuels, which is reasonable since the formation of these species is primarily thermally driven and the turbine exit temperature was maintained constant*."

This seems a defensible and widely applicable conclusion, which is that the use of a drop-in SAF fuel in an existing jet engine is likely to mean that the engine operates under thermal and gas throughput conditions that are very close to those for Jet A-1, since equivalent thrust and energy output would be required for the aircraft to operate. A consequence would be the same Zel'Dovich mechanism of formation for NO_x irrespective of fuel used. In some combustion settings, a lower heteroatom nitrogen content in fuels can lead to lower NO_x in exhaust arising from a reduction in the fuel-NO_x formation mechanism. However, for aviation applications, nitrogen content in fuel is already low, and a switch to SAF does not lead to any substantial change in fuel-derived nitrogen during combustion.

Implications: The adoption of SAF seems unlikely to lead to any substantial change in the emission of priority gaseous pollutants when compared to current fossil fuels. Modest reduction in CO emissions would be beneficial, but this is rarely a pollutant of direct local air quality concern in the UK. The VOC-related emissions from SAF are likely to be of a broadly similar absolute scale as fossil kerosene, although the speciation of those emissions in the engine exhaust may be different. This may have some implications for air quality monitoring strategies. Ambient air quality monitoring of mono-aromatics such as toluene and xylenes is relatively routine and these are part of existing fuels, and so can be detected as unburned emissions. SAF would not release these species but could plausibly lead to higher emissions of aldehydes and alcohols which are not routinely monitored. NO_x emissions are unlikely to change substantially with the introduction of SAF blended into Jet A-1. Reducing NO_x can be achieved through changing combustion conditions but typically this increases fuel burn and by extension raises overall CO_2 emissions. Even a pure SAF-fuelled aviation fleet seems likely to emit broadly the same amount of NO_x per unit of fuel used, since the emissions are linked most closely to combustion temperature and engine conditions rather than initial fuel composition. As NO_x emissions from other sectors fall, particularly from passenger road transport and energy production, aviation-derived NO_x is likely to grow in significance as a fraction of total national emissions.

The effects of this relative change in emissions between sectors on population exposure directly to NO_2 are complex. At present, road transport emissions occur often close to population centres and have roadside proximity effects making them disproportionately more important for health. Aviation NOx emissions in the lower atmosphere are frequently displaced from population centres, making direct exposure to NO_2 less likely. It is noteworthy however, that the WHO (2021) guidelines for annual average NO_2 exposure have been recently reduced from 40 mg m^{-3} to 10 mg^{-3}. Using the older 40 mg m^{-3} value, arguably aviation would play only a limited role in affecting future attainment in the UK. However, at the newer lower recommended limits, aviation emissions of NOx may become a significant factor influencing whether the WHO guidelines would be attained in London in the 2030s.

2.5 Hydrogen as an aviation fuel

Hydrogen has been mooted as a fuel for aviation for more than 70 years, with initial research into the use of liquid hydrogen as a jet fuel linked to space exploration and rocket design (Mulready,1964), and then later in the 1970s and 1980s was motivated by concerns about future stability and availability of oil supplies (Brewer 1982). Uses of hydrogen to directly address the climate impacts of aviation have been explored only relatively recently.

Older literature on emissions arising from the use of hydrogen in aviation are helpful, but of course are based on engine technologies that are not in use today. It is therefore difficult to directly extrapolate those results to possible future impacts of hydrogen in engines that in technological terms might be separated in design by close to 100 years. In more recent years the prospect of using hydrogen in fuel cells, to power fully electric, non-combustion flight has also been developed. For the purposes of this review, these technologies are not explored further since from a ‘point of use’ perspective they are effectively zero emissions of pollutants of concern to air quality and public health. The consequential impacts of fuel cell applications of hydrogen are of course supply chain emissions of other pollutants during production, the effects of slippage of hydrogen during transport, storage, and refuelling, and possible climate impacts arising from the emissions of water vapour at altitude. The wider atmospheric impacts of fugitive escape of hydrogen are not specific to aviation, and have been adequately covered in other reviews, see for example Derwent et al. 2006.

2.6 Emissions of NO_x

The use of hydrogen as a fuel in aviation engines is attractive from an air quality and air pollution perspective. The fuel is free of hydrocarbons, including aromatic compounds, and so burns with very low emissions of PM and BC. The fuel does not contain any sulphur, and so this further helps to reduce particle mass and particle number. A gas turbine cannot be completely free of hydrocarbons since they are needed for lubrication, but major reductions in emissions would be anticipated. Similarly, the removal of the carbon-based fuel eliminates CO emissions completely.

The key by-product from the use of hydrogen as a fuel in jet engines is the emission of NO_x, arising from the high temperature combustion conditions. There is significant crossover here in terms of principles with those described in Lewis and Wright (2022) report on H_2 combustion in compression ignition engines, and so it will not be repeated here. The basic processes that control NO_x in turbines have been known for many years (e.g. Heywood and Mikus, 1973). The amount of NO_x emitted when hydrogen is combusted is highly sensitive to the precise combustion parameters. Three key principles control the NO_x that is formed:

i) the throughput rates in the turbine, essentially how long very high temperature conditions are sustained for,

ii) the adiabatic flame temperature during combustion, and

iii) the mean equivalence ratio (whether the engine is running under lean or fuel rich conditions).

iv) Other effects such as the pre-mixing of fuel and air are also very influential.

Varying these parameters has dramatic effects on NO_x emissions and can lead to differences of several orders of magnitude in the amount of NO_x produced. Other examples support the proposition that NO_x is potentially a highly controllable by-product in exhaust. Dahl and Suttrop in 1998 achieved NO_x emissions that were nearly two orders of magnitude lower for hydrogen than kerosene through careful gas mixture and selection of combustion conditions. Other examples exist, and development work in this space continues today (e.g. Agarwal et al. (2019), who reported a 90% reduction in NO_x emissions from hydrogen fuelled aircraft turbines). However much of the development of the use of hydrogen is undertaken commercially and confidentially and there is a lack of peer reviewed data available in the public domain. This makes providing recommendations on the likely impacts of hydrogen as an aviation fuel to a degree uncertain, but there is at least evidence that NO_x emissions, the only major downside to the use of hydrogen, could be controlled if that was considered a high priority for manufacturers.

Implications: The ‘tunability’ of NO_x emissions means that levels of emissions in exhaust gases need active management via regulation and optimal emissions from an air quality perspective do not necessary emerge in engine design by default. If NO_x emissions are not a prime consideration, then it is plausible that aviation combustion conditions would be adjusted to give maximum energy efficiency and power output, and this may come at the expense of increased NO_x emissions, potentially up to the limits set out in existing regulations such as ICAO CAEP/8. There is long-standing evidence, such as Dahl and Suttrop in 1998, that the technological capacity exists to produce very low NO_x emissions engines, and that hydrogen fuel could help significantly improve air quality at the local level around airports. Hydrogen fuelling is without doubt an air quality opportunity, as would be battery electric or fuel cell aircraft.

2.7 Emissions of water vapour

A further emission arising from the use of hydrogen as a combustion fuel in aviation is the release of water vapour. Once at cruise altitude, the release of exhaust gases is followed by condensation of water (both from the exhaust and ambient air) due to low temperatures, the availability of co-emitted condensation nuclei via combustion PM, and these lead to the subsequent formation of contrails. These can persist and develop into longer lasting, line-shaped cirrus and more extensive cirrus cloud cover. The effects of individual persistent contrails can be warming or cooling but their net effect is understood to be a positive radiative warming (Lee et al. 2021). The combustion of hydrogen results in around 2.6 times more water vapour being released compared to the burning of kerosene, since the relative hydrogen content of the fuel is higher per unit energy. Water has radiative impacts as both a gas and when condensed as cloud droplets or ice particles. The overall lifetime of the water released is therefore very variable, lasting from a few days to up to a year depending on where the emissions occur (e.g. between upper troposphere and lower stratosphere), or whether in gas or cloud droplet state. The warming effects of additional water from hydrogen combustion are offset against the elimination of CO_2 emissions which has a much longer atmospheric lifetime, beyond 100 years. The net effects of this trade-off of reduced CO_2 for additional upper atmosphere water have been assessed by Ponater et al. 2006, who identified that overall, there was a net climate benefit, although this should be considered as an area where further research is needed to increase confidence in estimates of water vapour impacts (Clean Sky 2, 2020).

3. Conclusions and recommendations

3.1 Combustion and aviation

The decarbonisation of aviation is likely to follow multiple technological pathways, some of which may lead to very substantial air quality and air pollution co-benefits. Battery electric aircraft and fuel cell-powered aircraft have no point-of-use emissions and would generate improved air quality around airports. It is likely, however, that combustion and the use of turbine engines for aviation will persist for many years with either drop-in hydrocarbon fuels or hydrogen in aircraft specifically designed for this fuel. Both come with some air quality emissions, although these are potentially lower than those arising from use of current kerosene fuels.

- Sustainable aviation fuels (SAF) can be manufactured from a range of chemical engineering processes and are typically comprised of mixed branched and straight chain aliphatic hydrocarbons, have low aromatic content, and no sulphur. There is significant evidence that the use of this fuel in aircraft engines lowers the amount of non-volatile PM produced and black carbon. This is potentially an important air quality co-benefit and may also deliver climate benefits via reduced contrail and cirrus formation.
- The low aromatic and sulphur content of SAF is the key to its lower PM emitting qualities, so any substantial re-addition of these species to aid lubrication or engine performance could reduce this co-benefit. At present there are limits on maximum % blending of SAF into fossil kerosene, although it is unclear whether lubrication concerns lie behind this.
- Gaseous emissions from the use of SAF are broadly similar to emissions from kerosene fuelled aircraft. There is some evidence for modestly lower levels of CO emissions and for a change in the speciation of VOCs away from aromatic compounds to oxygenated compounds, reflecting that these emissions are linked to unburned fuel in the exhaust.
- Emissions of NO_x from SAF are anticipated to be broadly similar to existing Jet A-1 fuel, since the rate of formation during combustion is principally controlled by combustion temperature and the sweep time of the combustion chamber, neither of

which are expected to change significantly with the use of SAF. The retention of NO_x emissions in a future SAF aviation fleet would be the largest air quality disbenefit. From an air quality and public health perspective near airports, this would argue for the preferential use of battery electric or fuel-cell power aviation wherever that is feasible.

- The SAF impact of reducing PM emissions but retaining NO_x emissions is likely to have largest effects on those living near to airports, however the downwind effects (both benefits and disbenefits) should also be considered. This may be of some significance in London, where Heathrow airport lies immediately upwind.
- The use of hydrogen as a combustion fuel in aircraft turbines brings benefits to air quality through the reduction in emissions of PM and BC, as well as reduced emissions of CO, hydrocarbons, and of course CO_2. The impacts on NO_x emissions and resulting local air quality could also be beneficial if turbine combustion conditions were optimised for lower emissions. The use of hydrogen does however continue to lead to emissions of water vapour in the upper atmosphere during aircraft cruise which leads to radiative warming and that offsets some of the benefits from reducing CO_2 emissions. The climate impacts are an area of outstanding uncertainty that would benefit from further research.
- There is extensive evidence demonstrating that nitrogen oxides are released from hydrogen combustion, however this is a tuneable parameter and aviation-related demonstration projects provide confidence that very low NO_x engines are technologically feasible. If implemented these would bring considerable air quality benefits at the local level when coupled also to lower PM emissions. Specific regulation may however be needed for hydrogen engines to ensure they are optimised for more ambitious and lower NO_x emissions than are required in current ICAO regulations.

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