U.S. Department of Energy
Advanced Research Projects Agency – Energy

Announcement of Teaming Partner List for Upcoming Funding Opportunity Announcement: New Exploratory Topic in Aviation Contrail Predictive Systems

The Advanced Research Projects Agency – Energy (ARPA–E) is considering issuing a new Exploratory Topic under Funding Opportunity Announcements (FOAs) DE- FOA-0002784 and DE-FOA-0002785 to develop transformational technologies enabling real-time monitoring and predictive modeling of aviation condensation trail (contrails) that lead to the development of persistent cirrus clouds.[1] At cruise, jet engines from commercial aircraft may produce ice water contrails. Recent studies have indicated that contrail emissions may contribute to the creation of anthropogenic cirrus clouds that can be barriers to heat leaving the earth and contribute to global warming.[2] Proposals funded under this ET FOA will focus on ARPA-E's mission areas:

1. **Emissions Reduction**: Projects will develop the diagnostics and predictive tools needed to explore further mitigation of contrail-related global warming. If successful, a total radiative forcing emission equivalent to all CO_2 emissions from aviation can potentially be mitigated[2].
2. **Increase Efficiency**: As we consider potential future programs that explore the use and production of Sustainable Aviation Fuels (SAFs), this program will be important in increasing our understanding of water emissions from aviation jet engines.

Most contrails dissipate in a period of under 10 minutes and are of no concern. In rare occasions, when nucleation sites and specific atmospheric conditions exist (in particular ice super-saturated regions (ISSR)), the introduction of engine exhaust can result in persistent contrails, and further result in persistent cirrus clouds known as aircraft-induced cirrus (AIC).[3] These upper atmospheric clouds can last for hours and grow to span several hundreds of kilometers and are of specific interest.

ARPA-E envisions that an Aviation Contrail Predictive System, or Systems, capable of detecting and informing in real-time pilots and flight planning ground control whether an airplane is likely to produce persistent AIC could lead to R&D of a) future avoidance strategies – allowing re-direction of airplanes by ground control to more favorable (non-contrail) flight trajectories – and/or b) mitigation technologies to

[1] De Bock, P, "Leave No Trace!…. ….In the Sky", ARPA-E Innovation Summit 2022, https://youtu.be/lZ6iQHolab0?t=1487

[2] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A.The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244, p.117834 (2021).

[3] Kärcher, B. Formation and radiative forcing of contrail cirrus. *Nat Commun* **9**, 1824 (2018).

enable pilots to engage on-board contrail mitigation technologies. An Aviation Contrail Predictive System is particularly challenging, as AIC can form several hours after an aircraft has passed through a region.

The aim of this new Exploratory Topic is to develop a predictive model that in "real-time" and with high confidence could inform a pilot or flight operator whether an aircraft is producing an aircraft induced cirrus cloud, even hours before it is fully developed. It is anticipated that three technology areas need to come together to develop an Aviation Contrail Predictive System:

1. **Aircraft and environmental data and sensor development:** relevant data factors need to be identified and measured with sufficient accuracy. This might be a combination of aircraft speed, altitude, aircraft/engine model, fuel type, aerodynamic, humidity, pressure, weather forecast, or other relevant atmospheric data. If current sensors are insufficient, new sensors might need to be explored.
2. **Predictive modeling approaches:** It is anticipated that advanced predictive analytical methods are required or need to be developed to identify relevant parameters and develop correlations which can target a reasonably high accuracy, e.g., F_1-score > 0.8, strongly reducing the amount of false positives and false negatives.
3. **Observer data to validate and train the predictive model:** relevant observer methods need to be deployed, developed, or invented to provide feedback on whether aircraft contrails lead to AIC. This can be a set of ground observer systems near relevant flight corridors, aircraft mounted observing sensors, or space-based observer data. For the purposes of this new Exploratory Topic, limited relevant test flights for data gathering and model validation might be required.

Aircraft, Environmental Data and Sensor Development

New sensors or environmental data sources may be needed to provide sufficient training and validation data for the envisioned predictive capabilities. Contrail forming conditions are identified by the Schmidt-Appleman criterion: where water vapor content reaches liquid saturation under specific temperature and saturation conditions in the presence of nucleation sites.[4,5,6] Especially important are persistent contrails formed when airplanes travel through atmospheric ice super saturated regions (ISSR), leading to persistent aircraft induced cirrus (AIC) clouds.[3] As the persistent contrail formation regime is a combination of Schmidt-Appleman and ISSR criteria, sensors capable of identifying these parameters are of particular interest, e.g. sensor systems capable of measuring upper atmospheric humidity at or below 10 ppm.

Predictive Modeling

Advanced machine learning computational methods developed in the past decade allow the exploration of larger sets of input data and explore more complex multivariate correlations to solve complex problems than ever before. ARPA-E plans to explore if such methods can be used to develop a real-time predictive

[4] Appleman, H., 1953: The formation of exhaust condensation trails by jet aircraft. Bull. Amer. Meteor. Soc., 34, 14–20.

[5] Schumann, U., 1996. On conditions for contrail formation from aircraft exhausts. Meteorologische Zeitschrift, 5, pp.4-23.

[6] Teoh, R., Schumann, U., Majumdar, A. and Stettler, M.E., 2020. Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption. Environmental Science & Technology, 54(5), pp.2941-2950.

system for AIC development. To inform avoidance and mitigation strategies, it is important that developed predictive models give reasonably accurate results, minimizing false positive (type I) and false negative (type II) errors. This can be captured in the balanced F-score (F_1-score) which is the harmonic mean of precision and recall. A target for an F_1-score for AIC prediction system might be greater than 0.8 such that sufficient confidence exists to inform avoidance and mitigation solutions.

Observer Data

A predictive model needs to be trained and validated. For an Aircraft Contrail Predictive System this will likely require observers and additional sensors. It is anticipated that teams will need to obtain sufficient relevant flight and observer data from publicly available sources or dedicated flight observer tests to provide true AIC observations and validation rather than theoretical studies alone. Additionally, ARPA-E envisions a contrail reporting and observational data aggregation mechanism that mimics current tools for turbulence reporting and could further serve to continuously refine and improve AIC predictive modeling capabilities going forward.

ARPA-E seeks new and transformative solutions that can only be achieved by interdisciplinary teaming. Expertise in the following technical areas may be useful in responding to the potential Exploratory Topic FOA: Aerospace design, Aerospace Operations, Atmospheric Science, Sensing Technologies, Radar/Lidar systems, Flight Test capability, Aviation Propulsion, Aerosol Sciences, Combustion Sciences, Atmospheric Sciences, Observation Technologies, Machine Vision, Satellite Observation Systems, Machine Learning, Data Sciences, Predictive Modeling.

As a general matter, ARPA–E strongly encourages outstanding scientists and engineers from different organizations, scientific disciplines, and technology sectors to form new project teams. Multidisciplinary and cross-sector collaboration spanning organizational boundaries enables and accelerates the achievement of scientific and technological outcomes that were previously viewed as extremely difficult, if not impossible. Furthermore, ARPA-E strongly encourages involving industry partners to advise and collaborate with these project teams, with the goal of achieving successful industry adoption and integration of the innovative technologies these projects teams develop.

A Teaming Partner List is being compiled to facilitate the formation of new project teams. ARPA-E intends to make the Teaming Partner List available on ARPA–E Exchange (https://ARPA–E-foa.energy.gov), ARPA–E's online application portal, in December 2022. Once posted, the Teaming Partner List will be updated periodically, until the close of the Full Application period, to reflect new Teaming Partners who have provided their information.

Any organization that would like to be included on the Teaming Partner List should complete all required fields in the following link: https://arpa-e-foa.energy.gov/ApplicantProfile.aspx. Required information includes: Organization Name, Contact Name, Contact Address, Contact Email, Contact Phone, Organization Type, Area of Technical Expertise, and Brief Description of Capabilities.

By submitting a response to this Announcement, respondents consent to the publication of the above-referenced information**. By facilitating and publishing this Teaming Partner List, ARPA-E is not endorsing, sponsoring, or otherwise evaluating the qualifications of the individuals and organizations that are self-identifying themselves for placement on this Teaming Partner List. ARPA-E reserves the**

right to remove any inappropriate responses to this Announcement (including lack of sufficient relevance to, or experience with, the technical topic of the Announcement). ARPA–E will not pay for the provision of any information, nor will it compensate any respondents for the development of such information. Responses submitted by any means other than via the link provided above will not be considered.

This Announcement does not constitute a Funding Opportunity Announcement (FOA). No FOA exists at this time. Applicants must refer to the final Exploratory Topic, expected to be issued in February 2023 under the FOAs noted at the beginning of this Teaming Partner List, for instructions on submitting an application, the desired technical metrics, and for the terms and conditions of funding.