TECHNOLOGY COLLABORATION PROGRAMME (TCP)
EUWP ANNUAL BRIEFING

TCP NAME	Report Date
Sustainable Combustion TCP	03/14/24

Main Technology Policy Messages/Recommendations

Combustion supplies more than 80% of the global energy used in transportation, power generation, as well as industrial, commercial, and residential heat. As combustion continues to be a significant part of the world energy mix, it must be made sustainable with continued developments of technology and fuels. Advanced combustion technologies offer pathways for greatly reducing carbon emissions in all the major energy sectors.

- Policies requiring technologies with "zero" emissions of greenhouse gases or pollutants limit technology options and are likely to delay decarbonization efforts.
- Key combustion technology trends remain intact: a) increasing momentum in H_2 use for vehicle, stationary, and combined heat and power generation applications, b) increasing emphasis on sustainable aviation fuels (SAFs), and c) a strong emphasis on methanol and ammonia engines for the marine sector, with significant orders from industry for methanol engines.
- A roadmap for future fuels, supported by clear government policy commitments, is needed. Lack of it is a significant impediment to the decarbonization of combustion technologies.
- Improved and validated combustion system computational design tools continue to be a pressing need for developing/optimizing advanced clean and efficient combustion systems for sustainable fuels in all sectors.

Achievements

- The TCP Implementing Agreement (IA) was rewritten in 2022/2023 and approved by the IEA on 6/22/23 as part of the IEA TCP modernization project. Through the IA process the TCP name was formally changed to the Sustainable Combustion TCP to better reflect the new TCP research emphasis and directions.
- A Request for Extension (RfE) of the TCP for 5-years was granted by the IEA, extending the IA through 2/28/2029. Research during the extension will primarily focus on hard-to-electrify energy sectors that will continue to rely on combustion and on sustainable fuels with greatly reduced net carbon emissions. Continued research supporting reduction of pollutant emissions such as particulates, nitrogen oxides, and hydrocarbons will also continue to address urban health and social justice concerns.
- A reactor network-based modeling tool was developed to provide rapid estimates of how fuel composition and impurities, with a focus on SAFs, impact engine emissions and performance.

Dissemination and publications

- The TCP provided expert testimony in public webinars/workshops on the emissions and performance potential of H_2 ICEs and their place in both a transitional and long-term transportation energy system.
  - "Overview of Hydrogen Internal Combustion Engine (H2ICE) Technologies," HFTO, Feb. 22, 2023
  - "The future of H2 internal combustion engines in California?" and "H2ICE Impact on Medium and Heavy-Duty Track Applications," CARB, Nov. 28, 2023
- Prepared and presented "Sustainable fuels for a decarbonized future (in Spanish)" at the Conference Cycle Aida Fernández Rios of the Roya Academy of Sciences of Galicia (Spain) (May 2023).
- TCP visibility in the scientific community continues with extensive publications of TCP research in peer reviewed journals and presentations at conferences this year (approximately 80). See 2023 publications.

Collaboration and Co-operation

Other IEA network, TCPs, and co-ordination groups

- The Advanced Motor Fuels, Hydrogen, Bioenergy, and Combustion TCPs are collaborating on a white paper on Sustainable Fuels for combustion engines.
- Monthly SAF discussions were established. A presentation on the national lines of activities and competencies is being developed.
- IEA GREET+ Project: The Combustion, AMF, and H_2 TCPs are collaborating on a H_2ICE lifecycle analysis. Models for on-road and off-road vehicles are developed to quantify the energy consumption and incremental cost for new technologies. Output from vehicle models will directly inform the GREET analysis. We are relying on published H_2ICE maps for present analysis, but TCP partners have informed the team about their test plans for H_2ICE. More H_2ICE test data is welcome.
- Contributed to the H_2 combustion system TRL evaluations for the Hydrogen TCP TRL project (2023).

- Meetings/consortium/workshops involving TCP as leaders, organizers and/or participants: (a) 2nd Symp. on Ammonia Energy (7/11-13/2023 at Orléans, France), (b) 4th Workshop on "Solid Fuels Combustion" (6/24/23, 5 institutions and 13 participants), and (c) TCP public Annual Injection Processes Workshop (4/17/2023, SAE World Congress in Detroit, ~35 participants).

IEA Secretariat

- Two TCP delegates (P. Miles and A. Montanaro) attended the 5th Annual CERT/TCP Universal Meeting held 10/25-26/23 and the Transport Coordination Group (TCG) meeting held 10/24/23.
- Participated in IEA Experts' Group on R&D Priority-setting and Evaluation (EGRD) workshop on "Improving the resilience of the complete clean energy supply chains …" (12/12/23).
- TCP highlights presented at the Spring EUWP and Fall TCG meetings.
- Invited "IEA needs and priorities" presentations/updates continue by our desk officer at ExCo meetings.

Membership

- New member Italy fully integrated into the TCP. A delegate from Italy will serve as the Chair in 2025.
- New EU (Netherlands, Austria, and Poland), Australia, India, and China membership explored. A possible path has been found for China - IEA Legal to be consulted. Australia, Austria, and Poland are "no goes."
- Discussions on-going with several research groups in Spain to expand the number of institutions involved (*e.g.,* Univ. Zaragoza, Univ. Castilla Real, Univ. Valladolid, and Universidad Carlos III).

Management

- A task on exhaust aftertreatment for high-efficiency, low-carbon emission engines is in its final stages of development. Task presented at the Combustion TCP TLM (6/21/23) and the AMF TCP meeting (8/25/23). A 3-hour virtual task kickoff workshop was held on 11/22/23, with 4 guest speakers and 35 participants.
- A Strategy meeting and two successful ExCo meetings were held in-person.
- The 45th Task Leaders Meeting was held in Göteborg, Sweden on June 18-21, 2023. Each task held a technical session and a breakout session on future research plans. Fifty-seven researchers, program managers, and industry representatives from the 12 Combustion TCP member countries and others attended in-person with several more participating virtually. Fifty-eight technical presentations were given, including two invited keynotes on: (1) transition to fossil-free heavy-duty transport & (2) methanol as a marine fuel.
- Sprays in Combustion task renamed Injection Processes to reflect a new focus on gaseous fuel injection.
- New task leaders approved: System Analysis (Ram Vijayagopal, USA) and n-ZCET (Dario Lopez-Pintor, USA)

Outlook to the Future

- The combustion research emphasis in the transportation area has shifted to hard-to-electrify sectors, such as agriculture, construction, marine, rail, and aviation. Combustion based powertrains for heavy-duty applications will focus on optimized hybrid technologies.
- The fuel utilization emphasis continues to be on sustainable fuels (e-fuels, NH_3, H_2, methanol, biofuels, dimethyl ether, (poly) oxymethylene ethers, & others) for all land, sea, and air applications.
- Planned/anticipated external meetings: (a) TCP public Gas Engines Workshop (TBD, 2024), (b) TCP public Annual Injection Processes (Task) Workshop (April 16, 2024, SAE World Congress in Detroit), and (c) 5th Workshop on "Solid Fuels Combustion" (TBD, 2024).

TCP Meetings or Workshops (in-person)

2023 TCP Management Meetings			2024 TCP Management Meetings	
Place	*Date*		*Place*	*Date*
Paris, France (Strategy)	3/20/23		Paris, France (Strategy)	5/6/24
Paris, France (ExCo)	3/21/23		Paris, France (ExCo)	5/7/24
Göteborg, Sweden (ExCo)	6/22/23		Chicago, USA (ExCo)	8/8/24

TCP Annex/Task or Task meetings	Place	Date
2023 Annual TCP Task Leaders Meeting	Göteborg, Sweden	6/18/23-6/21/23
2024 Annual TCP Task Leaders Meeting	Chicago, USA	8/4/23-8/8/23

Annexes

There are nine subtasks under the overall Combustion TCP Task (Annex): (1) Systems Analysis, (2) Policy Briefs for Hydrogen and Its Vector Fuels, (3) *net*-Zero Carbon Engine Technology (n-ZCET), (4) Gas Engines, (5) Gas Turbines, (6) Soot, (7) Fuel Injection, (8) Solid Fuel Combustion, and (9) Combustion Chemistry. The APPENDIX provides details. A new task on Exhaust Aftertreatment will be considered for final approval at the May 2024 ExCo.

APPENDIX – Brief summary of Ongoing and Planned Annexes

Ongoing Annexes

Name	Objectives / Key deliverables	Launch /end dates	Countries	Key accomplishments, findings or lessons learned.
net-Zero, Carbon Engine Technology (*n*-ZCET)	**Objectives:** Provide fundamental combustion understanding to support co-development of ICEs and fuels in support of a transition from petroleum to renewable fuel sources with net-zero carbon emissions. **Key Deliverables:** Detailed scientific understanding and modeling tools required to design net-zero carbon emission ICEs.	2022-TBD	Finland France Spain Sweden USA	• A study of methanol use in a light-duty, compression-ignition engine showed: (1) A favorable NOx soot emissions tradeoff but with a penalty in CO and HC emissions. (2) Engine efficiency comparable to diesel above medium load. (3) Solving the poor low load operation is critical. (4) Well-to-wheels CO2 improvement depends on the methanol source. • Demonstrated operation of a production-like off-road compression ignition (Diesel) engine on ethanol and methanol with ignition improver. No additional hardware was required. Higher efficiency than diesel combustion noted at medium loads due to lower heat transfer losses. An efficiency penalty at low loads observed due to incomplete combustion. PM emissions were below US off road and HD limit. NOx was within the range of those for diesel fuel. • Studies of post-injections in a heavy-duty diesel coupled with a wave piston geometry showed that the combination can lead to significant improvement in fuel efficiency without increases in NOx emission. • Direct numerical simulations (DNS) is being used to explore the interaction between ammonia flames enriched with hydrogen and a solid wall. Understanding the details of the wall/ammonia flame interaction is critical to developing models for use in development of ammonia combustion systems.
Gas Engines	**Objectives:** Support the development of high-efficiency, ultra-low emission natural gas ICEs for surface transport and co-generation/grid balancing. **Key deliverables: a)** Characterization of advanced natural gas engine concepts offering efficiency and reduced emissions. **b)** Improved understanding of in-cylinder combustion processes required for design. **c)** Predictive computational engine design tools. **d)** New optical diagnostics for investigating in-cylinder natural gas combustion.	2014-TBD	Finland France Germany Japan Korea Spain Switzerland USA	• Experimental and numerical analysis of a methane-fueled, pre-chamber, spark-ignited gas engine show: (1) Large Eddy Simulation (LES) with detailed chemical kinetics can accurately predict the in-cylinder combustion phenomena. (2) The flame front contains compressed unburnt highly reactive radicals that lead to an accelerated combustion rate in the main chamber. (3) As pre-chamber gases enter the main chamber, they interact with the tumble flow to create additional turbulence. • Ignition studies in a large bore marine gas engine show that: (1) excess spark energy contributes to spark plug erosion indicating the need for "smart" ignition systems that deliver the right amount of energy at the spark gap to minimize wear; (2) AC ignition is better than DC in terms of electrode wear. • Investigating closed-loop combustion phase optimization to account typical natural gas fuel composition variations and cylinder balancing in a heavy-duty, spark-ignited ICE. Results showed the strategy is suited to engines operating under steady-state conditions. • Strategies and performances analysis of Diesel engines retrofitted to Spark Ignition Hydrogen Engines are being conducted for medium- and light-duty engines. Results demonstrated that Diesel engine-like performance can be reached with few modifications. The demonstrators could be driven

				on the road now. Further investigation of jet, mixing, combustion, and emissions needed for optimization. • Research on technologies for controlling particle emissions from modern heavy-duty gas engines showed: (1) Improved piston ring pack design can result in a large reduction in particulate number (PN) by influencing the reverse ring blow by process; (2) Changing the oil formulation further decreased the PN; and (3) Installing a particulate filter in the exhaust line provided very efficient PN abatement. • Laser Induced Fluorescence (LIF) and OH* imaging of in heavy-duty DI H2 engine with a central hollow-cone medium-pressure injector have provided detailed understanding of H2 injection timing and pressure on mixture formation on combustion and data for CFD simulation validation. Over the range of parameter variation, injection timing impacts combustion speed the most, injection pressure and ignition location impact it much less. • Research on hot spot and oil induced pre-ignition mechanisms in H2 fueled heavy-duty engine showed: (1) Temperatures exceeding 1100 K are needed to trigger pre-ignition, primarily at low in cylinder pressure. Kinetic simulations explained the phenomenological observations and highlighted a potential mitigation pathway using late DI and high intake pressure. (2) H2 tends to have a stronger pre-ignition inhibitive effect at low concentrations while exhibiting a saturation effect at high concentrations. Kinetic simulations indicate a strong shift in the most reactive mixture fraction to richer regions. • New engine test facility (Flex-OECoS) established for investigating carbon-reduced combustion concepts using H2, H2/CH4, NH3, MeOH, synthetic and renewable fuels (PtG, PtL) using optical diagnostics at relevant engine load conditions. • Direct numerical simulation of laboratory scale engines at realistic engine speeds using exascale computing are being employed. Results are showing that the dynamically changing momentum and thermal boundary layers in engines are far from ideal, identifying weaknesses and quantify deviations from current modelling assumptions, and providing data for new model near wall model development.
Gas Turbines	**Objectives**: Develop combustion technologies for high-efficiency, ultra-low emission gas turbine engines for power generation, industrial processes, and air and sea transport. **Key deliverables**: **a)** Combustion understanding needed for adoption of low carbon fuels (*e.g.*, CH_4/H_2 mixtures and H_2-carrier fuels like ammonia and methanol) and for extending the operational limits with these fuels. **b)** Improved predictive models for gas turbine design.	2014-TBD	France Japan Norway Spain Sweden Switzerland UK USA	• Demonstrated gas turbine operation from cold start to power generation solely on ammonia fuel. This was accomplished using partially reformed gaseous NH3 during start-up then phasing to full liquid ammonia operation for power generation using a precombustion zone. Unburnt NH3 and N2O emissions shown to be an important issue. • Developed a high-fidelity soot modelling strategy from chemical kinetics to turbulent combustion. Model successfully used for soot modelling in laminar flame canonical configurations up to a single sector aero GT like turbine combustor. • Showed that for all CH4-H2 fuel compositions under gas turbine like conditions: (1) Pressure in the 2.5-7.5 pressure range has a weak effect on turbulent flame speed, flame length, and flame brush size, and (2) flame speed increases with H2

				concentration with a large factor of 4 change between 50% and 100% hydrogen. • Investigated various ways of promoting NH3 flame speed that included CH4 and H2 addition and reformation of NH3. Details suggest that turbulent flame speed behavior correlates with added fuels, but flame morphology has different flame structures that are highly stretched and non-spherical.
Soot	**Objectives: a)** Advance the scientific understanding of soot formation/ oxidation processes for enabling prediction of detailed soot characteristics for various fuel and for aiding the design of systems with highly reduced soot emissions. **b)** Expand the understanding of how soot toxicity and environmental impact change with fuel and combustion concept. **Key Deliverables: a)** Predictive soot models describing the detail-ed formation processes. **b)** Engineering soot models that are sufficiently accurate for combust-ion system design optimization. **c)** Characterization of the effects of engine parameters on soot formation, oxidation, and emissions.	2014-TBD	Germany Korea Spain UK USA	• Studies aimed at characterizing the properties of soot generated by combustion of sustainable aviation fuels under conditions relevant to modern and next generation aero engines initiated. Soot particle and aggregate sizes, detailed soot structure and molecular composition are being investigated. • A study to understand the injection, mixing, and autoignition of e-fuels for CI engines was initiated. Polyoxymethylene Dimethyl Ether 3-5 ($OME_{3\text{-}5}$) used as a representative e-fuel was shown not to form soot under any conditions. Its basic fuel injection, spray, and combustion characteristics relative to a reference hydrocarbon fuel (n-dodecane) were measured and compared. • Detailed kinetic modeling of soot and soot precursors for low lifecycle carbon fuels for use in aviation, off-road, rail, and marine sectors initiated. The goals are understanding and models for use as advanced computational design tools for developing low life cycle carbon combustion systems. • A soot prediction framework is currently being developed to estimate soot particle number (PN), particle mass (PM), and particle size distribution (PSD) of particulate emissions from GDI engines. An injector tip fuel evaporation model approach has been coupled with a particle emission framework. The focus is on carbon neutral fuel use.
Injection Processes	**Objectives:** Advance the fundamental understanding of spray formation and mixing and the capability for computationally designing fuel and air mixing processes in combustion systems with fuel sprays. **Key Deliverables: a)** Improved understanding of the influence of sprays on advanced combustion strategies that promise clean, highly efficient ICEs. **b)** Advanced state-of-the-art of computational tools for sprays relevant to engine designers.	2014-TBD	Finland France Germany Japan Korea Spain Sweden Switzerland USA	• Task was renamed from “Sprays in Combustion” to “Injection Processes” to reflect growing gaseous fuel (*e.g.*, H2, CH4, NH3) injection research. • New X-ray diagnostic capabilities demonstrated for investigating a variety of fuel injection (*e.g.*, nozzle hole wear and deposit formation), gaseous hydrogen fuel jet processes, sustainable aircraft turbine-type fuel injection processes, and urea injection processes for NOx emission abatement. • Investigation of ammonia fuel injection process initiated. Studies are looking at spray morphology, spray development, and fuel vaporization processes, including flash boiling. • Injection of gaseous fuels often involves under-expanded jets. These jets are being investigated for application in advanced propulsion systems. Results so far show that: (1) multi-hole injectors need to be properly designed to avoid hydraulic losses that arise due to energy dissipation from shock wave onset; (2) H2 and CH4 jet morphology can be significantly different even if they are injected in the same conditions; and (3) the H2 and CH4 jet flow field differences drive different turbulent mixing process for each of these fuels. • New research on the role of extreme conditions in aero-engine on spray processes using a single-hole atomizer initiated. High speed, long-distance

				microscopy experiments coupled with machine-learning algorithms were employed to investigate the evaporation regimes of fuels. The results show that classical and diffusive evaporation regimes can co-exist. However, in agreement with past work is the fact that surface tension is still very relevant across all but the most extreme conditions. • Experimental and numerical studies initiated on medium-pressure hydrogen jets and mixing process Results will help design optimal injectors for retrofitting current technology Diesels to spark-ignited hydrogen engines. • A study to develop two-color, inexpensive, inorganic fluorescent tracers for advancing the measurement of gaseous flows and temperature in engines was initiated. Initial results using SiO2 dyed with fluorescent dyes are promising. • Large Eddy Simulation of reacting methanol spray flames providing new understanding of methanol fuel jet ignition and development under compression ignition engine conditions. Results include showing that methanol ignites in lean spray regions unlike typical diesel-type fuels which ignite in rich regions.
Solid Fuel Combustion	**Objectives:** Provide a better understanding of solid fuel combustion that is required to develop more flexible, cleaner, and efficient combined heat and power systems. **Key Deliverable**s: **a)** Improved design concepts for solid-fuel combustors. **b)** Advanced models for solid fuel gasifier or combustor design. **c)** Advanced process monitoring sensors.	2014-TBD	Germany Spain Japan	• Eulerian Biomass Thermal Conversion Model shown to predict reasonably accurately solid fuel bed distribution and temperatures. Results show that lower primary air ratios and higher secondary air ratios result in more uniform combustion and lower peak temperatures. Also, flue gas recirculation in the tertiary air can reduce unburned emissions and peak temperatures in the furnace upper chamber. • Initiated development of a CFD model of flow through beech wood particles using a realistic geometry based on µ-CT imaging. • Project initiated on chemical recycling of plastics for chemicals production in the framework of circular economy. Products in gasoline- and diesel-like fuel spectra possible. Suitable catalysts identified, further improvement in them possible.
Combustion Chemistry	**Objectives:** Develop and validate chemical kinetic models for renewable fuels (including blends with petroleum fuels) for optimizing combustion devices. **Key Deliverables: a)** Validated kinetic models. **b)** Quantitative species concentration, flame speed, and ignition delay data to support model development. **c)** Identification of important oxidation pathways needed for model development.	2014-TBD	Finland France Japan Sweden Switzerland USA	• Chemical kinetic model development has shifted largely to models for low lifecycle carbon fuels. • Fundamental experiments and modeling aimed at improving models for hydrogen and ammonia fuels for zero-carbon aviation and power generation systems are underway. Initial results suggest (1) models need improvement for lean and rich natural gas conditions; (2) at 50% H2, H2 combustion chemistry dominates when added to HC fuels while NH3 addition shows no effect; and (3) NH3 addition to current natural gas gas-turbines looks promising without needing a major infrastructure change. • New detailed chemical kinetic ignition modeling and experiments are showing that important reactions of resonance-stabilized radicals with O2 are underestimated (or ignored) reactions in many autoignition and combustion models. • Progress made in identifying simplified surrogate fuels that reasonably well simulate the physical and chemical properties of various potential sustainable aircraft fuels (SAFs). Detailed chemical kinetic models developed and validated for surrogate fuels

				can then be used to develop skeletal chemical kinetic models of SAFs for use in CFD system design tools.
Policy Briefs on Hydrogen and Its Vector Fuels (PB-HVF)	Objectives: Research hydrogen and its vector non-carbon fuels (e.g., ammonia) for end-use combustion technologies. Key Deliverables: Expanded knowledgebase on non-carbon HVFs utilization required to develop efficient, clean end-use HVF combustion technologies.	2022-TBD	UK Others TBD	• Survey of the state of interest, status, and plans for fuels such as hydrogen, ammonia presented at the TLM. Preliminary conclusions included: (1) ”Policy” does not match the ”plan” for these fuels; (2) For the power sector, gas turbines seem to be the ’safest bet’ for the use of hydrogen and ammonia and its vector fuels; (2) For the marine sector, internal combustion engines seem to be the ‘safest bet’ for the combustion of ammonia and, in some niche markets, hydrogen; (3) For trucks, the ‘jury is still out’, but H2 combustion has not been ruled out. • Orgaized, led, and particpated the 2nd Symposium on Ammonia Energy in Orleans France (2023). • Continued providing leadership and participation in the FLEXnCONFU Consortium on non-conventional fuels (H2 and NH3) for power generation.
Systems Analysis	**Objectives:** Determine the trade-offs between technology solutions, energy security, and greenhouse gas (GHG) emissions for the transport and energy production sectors. Analyze the most realistic solutions for cost and time effective decarbonization. **Key Deliverables:** Expand the knowledgebase on technology and renewable fuel effects on present and advanced future systems, and deliver system level data, tools, and know-ledge for effective decision making.	2022-TBD	Finland France Germany Japan Korea Norway Spain Sweden Switzerland USA	• New task leader approved for this task - Ram Vijayagopal, USA. • Continued to participate in the DOE/IEA GREET+ project to develop a consistent and comparable LCA modeling platform to examine GHG effects of different technologies in different global regions. In collaboration with the AMF TCP and the Hydrogen TCP, this task is focused on providing data to GREET+ for LCA of hydrogen-fueled, heavy-duty ICEs. • Summary of the GREET+ project systems modeling tools and status of the overall project presented at the task TLM session.

PLANNED ANNEXES

Name	Expected objectives / Key deliverables	Launch date	Potential Participants	Main planned activities (Details TBD)
Exhaust After-treatment	**Expected Objectives:** Provide the understanding of aftertreatment systems (ATS) required to optimally develop and match ATS, engine and future low-carbon or decarbonized fuel options. **Key Deliverables:** Improved technology, data, design models.	TBD	TBD	• Task scope was presented the 45th TLM in Sweden on June 21, 2023 by the Task development leader, Daniel Peitz. • Preliminary approval for this new task given by the TCP ExCo on June 22, 2023. • Initial stakeholder/participant workshop held November 22, 2023. Task plan to be present and voted on for final approval at the May 7, 2024 ExCo in Paris. • Research will focus on aftertreatment systems to further reduce emissions in systems using advanced high-efficiency combustion strategies and/or low carbon/decarbonized fuels.