TECHNOLOGY COLLABORATION PROGRAMME (TCP)
EUWP ANNUAL BRIEFING

TCP NAME	Report Date
Clean and Efficient Combustion (Combustion TCP)	2/13/2023

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.

- 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.
- Combustion research must continue to support advanced combustion technology development. A major part of the research should focus on hard-to-electrify energy sectors that will continue to rely on combustion and sustainable fuels that provide greatly reduced, net-zero, or zero-carbon emissions. Research supporting continued reductions in pollutant emissions in all sectors (*i.e.,* particulates, nitrogen oxides, and hydrocarbons) will also be necessary for addressing urban health and social justice concerns.
- Key trends impacting combustion technologies include: a) increasing momentum in H_2 use for vehicle, stationary, and combined heat and power generation applications, b) increasing emphasis on sustainable aviation fuels, and c) a strong emphasis on methanol and ammonia engines for the marine sector, with significant orders from industry for methanol engines.
- Fuel injection equipment, including injectors, high-pressure on-board pumps, cryogenic pumps, and tender couplings are key technology gaps impeding faster penetration of H_2 combustion technologies.
- Premature ignition, flame flashback, and higher NOx and/or aldehyde emissions are major concerns with combustion of several alternative fuels (*e.g.*, hydrogen, ammonia, and methanol).
- Thermal runaway/battery fires are a critical intersection between the combustion and electrification fields.
- Fundamental knowledge gaps in sprays, chemical kinetics, transient heat transfer, ignition processes, and pollutant formation (soot, NOx) are impeding development of optimized combustion technologies.

Achievements

- A survey of the combustion research trends and needs in each TCP member country was completed. The survey helped continue the transition of the TCP toward research in support of sustainable combustion.
- Natural gas combustion in a pre-chamber ICE with various ignition systems showed considerable potential for improved performance and efficiency, and reduced emissions (including CO_2), relative to current ICEs.
- Key n-ZCET Task results included: a) quantification of the impact of oxygenated low-carbon fuels on cold-start emissions, b) new understanding of the synergies between soot reduction technologies, such as ducted fuel injection, and renewable fuels, c) technologies for enabling more efficient use of methanol and ethanol, and d) development of strategies to overcome the poor combustion characteristics of ammonia.
- Simulations and experiments have shown that soot formation in gasoline direct-injection engines is mainly derived from interactions that occur when liquid droplets from fuel injection impinge on surfaces. This understanding is critical for accurately predicting soot formation and soot loading on particulate filters.
- Studies to-date have now confirmed that gas turbine operation with natural gas mixtures containing up to 20-30% H_2 has limited impact on efficiency and operation, and can be a first step into a H_2-based economy.
- With optimized staged-combustion and pre-cracking of NH_3 into H_2 and N_2, a substantial reduction in NOx emissions can be achieved for all NH_3 applications (engines, turbines, furnaces, and process heaters).
- Kinetic mechanisms were developed for soot precursor formation and behaviors of low-carbon fuels such as light alcohols and ammonia-hydrocarbon blends.

Dissemination and publications

- TCP visibility in the scientific community continues with extensive publications of TCP research in peer reviewed journals and presentations at conferences. The average is about 100 publications per year. See https://www.ieacombustion.com/meetings-publications/tcp-publications/ for 2022 publications.
- Solid Fuels Task biomass combustion models were disseminated to researchers and institutions worldwide.
- TCP researchers participated in the formation and leadership of a new consortium dedicated to power generation with carbon-free fuels (https://flexnconfu.eu/about/consortium/).

Collaboration and Co-operation

Other IEA network, TCPs, and co-ordination groups

- IEA GREET+ Project: The Combustion, AMF, and H_2 TCPs are collaborating on a lifecycle analysis (LCA) of hydrogen ICEs. Our TCP is focused on improving efficiency, refining load speed maps, and minimizing precious metal use in aftertreatment. The TCP held five on-line meetings and participated in two GREET+ workshops. Michael Wang from Argonne National Lab gave a GREET LCA modeling overview at our TLM.
- Meetings/consortium/workshops involving TCP as leaders, organizers and/or participants: 1st Symposium on Ammonia Energy (Sep. 1-2, 2022, Cardiff, UK, ~300 participants), and the TCP public Annual Spray Workshop (April 4, 2022, SAE World Congress in Detroit, ~40 participants).

IEA secretariat

- TCP highlights presented at the Spring EUWP and Fall TCG meetings.
- Participated in the first IEA Critical Minerals TCP Coordination Group meeting December 8, 2022.
- IEA "needs and priorities presentations and updates" continue by our desk officer at our ExCo meetings.

Membership

- Italy became a member of the Combustion TCP in the Fall of 2022, bringing the country participation to 12.
- New EU partners (Netherlands, Austria, and Poland), India, and China membership continues being explored. The latter two especially will require early IEA HQ involvement if opportunities develop.

Management

- A task on exhaust aftertreatment for high-efficiency, low-carbon emission engines is being explored. This task would complement existing TCP activities. A vote on the task is expected at the March ExCo meeting.
- A Strategy meeting and two successful ExCos were held in-person. They also included virtual attendance.
- The 44th Task Leaders Meeting (TLM), hosted by Japan, was held in a hybrid format (in-person & virtual) from July 31 to August 4, 2022, in Sendai, Japan. Each task held a session. Twenty-six researchers and program managers from Combustion TCP member countries attended in-person daily and another approximately 15 participated virtually daily. More than 45 technical presentations were given.

Outlook to the Future

- Research emphasis in the transportation area continues to shift toward 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.
- Increased emphasis on sustainable fuels (e-fuels, ammonia, hydrogen, methanol, biofuels, dimethyl ether, (poly) oxymethylene ethers, & others) for all combustion applications, including maritime and aviation.
- Aviation soot emissions receives attention as a potentially greater climate forcer than CO_2 from aviation.
- Planned external meetings: TCP public Gas Engines Workshop in 2023 or 2024, TCP public Annual Spray Workshop (4/17/2023, Detroit, USA), and 2nd Symp. on Ammonia Energy (7/11-13/2023, Orléans, France).

MEETINGS OR WORKSHOPS (hybrid = in-person and virtual attendance)

2022 TCP Management Meetings			2023 TCP Management Meetings	
Place	*Date*		*Place*	*Date*
Berlin, Germany (Strategy) (hybrid)	4/25/22		Paris, France (Strategy)	3/20/23
Berlin, Germany (ExCo) (hybrid)	4/26/22		Paris, France (ExCo)	3/21/23
Sendai, Japan (ExCo) (hybrid)	8/4/22		Göteborg, Sweden (ExCo)	6/22/23

CURRENT AND FUTURE ANNEX OR TASK MEETINGS

TCP Annex/Task	Place	Date
2022 Annual TCP Task Leaders Meeting (hybrid)	Sendai, Japan	7/31/22-8/4/22
2023 Annual TCP Task Leaders Meeting	Göteborg, Sweden	6/18/23-6/22/23

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) Sprays in Combustion, (8) Solid Fuel Combustion, and (9) Combustion Chemistry. The APPENDIX provides further details. One new task on Exhaust Aftertreatment task remains under consideration.

APPENDIX – Brief summary of Ongoing and Planned Annexes

ONGOING ANNEXES

Name	Objectives / Key deliverables	Launch /end dates	Participants	Key accomplishments, findings or lessons learned.
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	This task is new and continues to develop research directions and collaborations. Recent accomplishments include: • In collaboration with the AMF TCP and the Hydrogen TCP, participating in a project focused on the GREET+ life cycle analysis (LCA) of hydrogen-fueled, heavy-duty, internal combustion engines. • Participated in 2 workshops (ETSAP and GREET+) • Arranged 5 on-line task workshops/ meetings (5 to 10 participants). • Participated in the IEA TCP Critical Minerals Coordination Meeting.
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	This is a new task. Efforts are proceeding to integrate this task with other TCP tasks. To date, the primary contributions include supporting the leadership, organization and participation in the 1st Symposium on Ammonia Energy (2022), the 2nd Symposium on Ammonia Energy (to be held in 2023), and the FLEXnCONFU Consortium on non-conventional fuels (H_2 and NH_3) for power. The FLEXnCONFU is evaluating hydrogen and ammonia combustion performances through research at Cardiff University on different ammonia/methane/hydrogen fuel blends. Tests outcomes will provide knowledgebase required to modify gas turbines for ammonia and hydrogen utilization.
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	• Assessed how an updated compression ignition (CI) engine calibration can enable clean and efficient combustion using up to 100% renewable fuel. • Quantified fuel effects on catalyst-heating operation for lean CI operation using low-carbon fuels like biofuels, Oxymethylene Dimethyl Ethers (OMEx), Di-Methyl Ether (DME) and alcohols. • Demonstrated the use of Ducted-Fuel Injection (DFI) to suppress soot formation by factor of 100 in a CI engine operated on fuels with high levels of renewable fuels. • Explored operating strategies and engine configurations to ensure reliable autoignition for a low-reactivity fuels, such as methanol, enabling efficient CI operation. The use of a very high compression ratio (40) is one pathway, but it may lower the load capability of the engine due to excessive peak pressures. The use of glow plugs, intake air heating and pilot injections provide other pathways for

				operation with higher loads and a conventional compression ratio. • Developed knowledge on how to overcome the inherent low flame speed of ammonia and improve spark-ignition (SI) engine operation. For operation with neat ammonia, increasing the compression ratio to 17 can enable stable operation. For lower compression ratios, H_2 or ethanol addition is necessary to ensure stable combustion.
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	• Advanced a model for predicting learn-burn ignition in spark-ignition (SI) engines that included: a) Developing a successful method for accounting for thermal plasma effects. b) Successful prediction of spark channel elongation and re-discharge for non-reaction conditions. • Models and experiments demonstrated optimal high-BMEP (3 MPa) performance in a natural gas, pre-chamber engine without abnormal combustion. • In-cylinder H_2 direct-injection mixing characterization experiments were performed in a heavy-duty optical engine. Preliminary results suggest: a) An outward opening hollow-cone injector jet rapidly collapses, and jet evolution is impacted by shock structure and in-cylinder density. b) Early injections create a more homogeneous mixing field; late injections create stratified mixtures. c) Injection pressure is important for mixture stratification. d) Cyclic variability of mixture is very high for all injection timings except when injecting during the intake stroke. e) Non-quiescent combustion chambers may improve the repeatability of mixing. • Established Exhaust Gas Recirculation (EGR) operation limits and highlighted the limiting factors for a natural gas, heavy-duty prechamber operation: a) Jets exiting the pre-chamber appear to extinguish at reduced O_2 concentrations and late spark timing. b) Failed re-ignition of pre-chamber jets is the main cause of combustion variation and misfire for conditions tested. c) Slower pre-chamber combustion at low O_2 reduces the main-chamber heat release rates – limiting efficiency gains. • The hydrogen jet dynamics for an outward opening piezo-injector, a modified single hole injector, and a special hydrogen injector with different caps were measured with high-speed schlieren imaging at various engine-like conditions. Results show: a) A H_2 jet has a similar behavior as CH_4 and helium jets. This suggests that the current gases injection systems for CH_4 might be suitable for H_2 injection. b) The injector location and jet direction are important for the fuel-air mixing processes. Preliminary considerations suggest that smaller injection angles (10° or 15°) might lead to the most balanced final mixture. c) The

				process of hydrogen premixed combustion is strongly controlled by the gas-air mixture and boundary conditions (*e.g.*, equivalence ratio, temperature, and pressure). • Demonstrated that spark-ignition for port fuel injected hydrogen in medium-duty commercial diesel engines and direct-injection in light-duty commercial engines can achieve Diesel Engine performance with few modifications.
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	• Ammonia can be used to decarbonize cooling, heat, power, and propulsion generation. Initial research suggests that ammonia blends can be used efficiently, with low NOx. • Initial ammonia gas turbine (GT) research results: a) 50kW-class Micro Gas Turbine (MGT) operated with liquid ammonia. b) Gas ammonia ignition demonstrated in a swirling burner. c) Liquid ammonia sprays investigated. • Demonstrated flame holding at one GT condition with Micro Impinged Jet Array (MIJA) Burner for non-premixed hydrogen oxygen combustion. • Helped lead, organize and participate in the formation of Competence cEntre on Sustainable Turbine fuels for Aviation and Power (CESTAP) at Lund University involving 26 industry partners. The consortium is focused on sustainable turbine fuels for power and electricity production, and for aviation propulsion. The vision is to transform aviation and power generation sectors to run continuous combustion engines on 100% sustainable turbine fuels. • Flame development and stability are critical NH_3 fuel issues. Fundamental research has advanced the detailed understanding of turbulent-flame interactions for NH_3-based fuels.
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	• Simulations and experiments showed that soot formation in gasoline direct-injection engine combustion is mainly derived from interactions where liquid droplets from fuel injection impinge onto surfaces. This understanding is critical for accurately predicting soot formation and soot loading on particulate filters. • Formed new collaborative projects to estimate soot formation in gas turbines and to characterize Particulate Mass and Particulate Number in the exhaust. Area will be become one of the primary focuses of the task in the next five-year term. • Simplified models for coupling soot formation with complex computational fluid dynamics simulations were conceived for computationally efficient design of gas turbines.

Sprays in Combustion	**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	• Laser based experimental measurements and Large Eddy Simulations (LES) are providing in-depth understanding of ignition and combustion processes in high-pressure spray flames. a) LES showed the first and second stage of ignition location and timing; b) Experiments and LES showed CH_2O consumption leads to high-temperature ignition kernels at the jet periphery; c) Mixture analysis in conjunction with formation/consumption of CH_2O and OH investigation revealed that CH_2O substantially decreases for Φ <3, leading to high temperature flame stabilization; d) LES mixture analysis also showed CH_2O in the center of the jet (x>20 mm and Φ>6) are formed and consumed at a 6-kHz period. The same phenomenon was observed in the experiments; e) The periodic oscillation of CH_2O suggests acoustic cool flame wave coupling in the chamber. • Emissions caused by cylinder surface fuel wetting under cold start conditions motivated the investigation of gasoline direct-injection fuel spray wall impingement using Computed Tomography (CT) analysis, optical measurements of fuel impingement, and time resolved surface heat flux measurements. The results are informing improved modeling approaches by providing detailed impinging spray characterization, quantitative measurement of fuel film thicknesses, and surface heat fluxes for various conditions. • LES of diesel spray combustion coupled with an interior wall heat conduction model are providing improved understanding and models for diesel combustion systems. • Diesel spray visualization and Phase Doppler Anemometry (PDA) measurements demonstrated how the accuracy of PDA data can be improved.
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	Our research has made significant progress in understanding the complex role of particulates in both gasification and combustion, using a combination of modeling, experiments, and machine learning techniques. As a result of our efforts, we have developed a comprehensive solid-biomass combustion model that has attracted widespread interest and collaboration from researchers and institutions around the world. In addition, we have expanded a collaborative network between the University of Vigo, TU-Berlin, German Biomass Research Center (DBFZ) to include Otto-von-Guericke-University Magdeburg. The collaboration is working on the conversion and revalorization of biomass. These efforts have resulted in important advances and have contributed to the scientific community.

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	• Detailed chemical kinetic simulations coupled with experiments have revealed the effects of temperature on soot precursor formation for promising oxygenated fuels (*e.g.*, methanol, DME, OME, 2-Methylfuran) blended with diesel-like fuels. A pronounced increase in soot precursor production occurred at a lower temperature when oxygenated fuels are blended in, while this effect was diminished at an elevated temperature. The results revealed detailed kinetics behind these temperature effects. • Chemical kinetic studies on the impact of carbon-neutral fuels on lean SI combustion have provided understanding of how these fuels affect the lean limit of combustion, and how the changes relate to known properties like octane sensitivity & fuel molecular weight. • Model development and validation for linear carbonate esters is advancing. These esters are important in diesel fuel additives, bio-derived fuels, and a potential cause of lithium battery fires. Oxidation and pyrolysis characteristics of one easter, diethyl carbonate (DEC), were examined using a micro-flow reactor. Results have provided understanding of the effects of temperature on oxidation and pyrolysis and the multiple stages of these processes.

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	Research aftertreatment systems in combination with advanced high-efficiency combustion strategies and future low-carbon/decarbonized fuels to further reduce engine emissions. Vote to adopt or not adopt this task is expected in 2023.