TECHNOLOGY COLLABORATION PROGRAMME (TCP)
EUWP ANNUAL BRIEFING TEMPLATE

TCP NAME	Report Date
Clean and Efficient Combustion (Combustion TCP)	02/20/2021

Main Technology Policy Messages/Recommendations

Worldwide, more than 80% of the energy used is converted by combustion to usable forms for transportation, power generation, and industrial, commercial, and residential heat. Combustion will continue to be a significant part of the world energy mix for the foreseeable future and needs to be made sustainable with continued advancements and low-carbon fuels.

- **There is a need for "real world" vehicle life cycle analyses that account for the adoption of new technologies on carbon emissions as a function of time to better understand short-to-intermediate term policy impacts.** For example, analyses show that given the need to reduce green-house gases (GHG) quickly, the current regulatory posture in the U.S. of allowing additional CO_2 emissions in the near term to lay the foundation for potential future reductions may not be advantageous. (See https://doi.org/10.1016/j.tra.2019.04.003)
- **Quickly reducing GHG by electrification is limited not only by technology, but also by slow vehicle fleet turnover time. Faster reductions may be achieved by substituting fossil fuels with sustainable, renewable drop-in fuels**. See for example: https://www.imeche.org/news/news-article/better-petrol-engines-and-fuels-'the-quickest-way-to-cut-emissions?utm_campaign=1837346_DV_Automotive_Feb20&utm_medium=email&utm_source=dotdigital&dm_i=3X32,13DPE,2ZV149,3TO2V,1
- **A combination of technologies – including use of emerging alternative fuels, advanced combustion strategies, hybridized vehicles with internal combustion engines (ICEs) and pure battery electric vehicles – will be required to meet 2050 CO_2 reduction targets**.
- **Renewable chemical energy carriers (such as hydrogen), which allow for long-term energy storage relative to batteries and thermal energy storage, show considerable potential for addressing growing seasonal energy imbalances in electric grids caused by increasing electrification of mobility and domestic heating applications**. Use in combined heat and power generation is one important application.
- **Existing power generation systems using gas turbines or ICEs are continuing to be qualified on increasingly higher concentrations of hydrogen (H_2) blended with natural gas to pave a path for early adoption of hydrogen to achieve immediate reduction of GHG emissions.** Gas turbines provide quick response to electrical load variations and thus play key a role in grid stabilization. All major gas turbine manufacturers have announced that H_2 in natural gas can be tolerated at levels up to 20-30% vol. (in single cases up to 50% vol.). Further research will advance the use and impact of H_2 on lowering GHG emissions.
- **The use of H_2-carrier fuels (*e.g.*, ammonia (NH_3), methanol) continues to be a subject to intense R&D.** This is especially true for NH_3, which can be burned directly as NH_3 or decomposed to H_2 and burned as H_2. Land-based power generation using gas turbines and marine and heavy-duty truck transportation using ICEs are currently the main NH_3 applications being considered.

Achievements

Scientific focus

- Building upon a U.S. DOE EIA analysis to understand the overall effects of various light-duty vehicle technologies on the fleet, the need for both electrification and increased ICE efficiency to meet 2050 light-duty CO_2 reduction targets was demonstrated. Additional funding is being sought to study in further detail.
- Significant advances have been made in simulating fuel injection with low-carbon fuels, including the development of a new, more accurate evaporation model and better treatment of flash-boiling processes.
- The combustion characteristics of methane-H_2 blends have been determined at gas turbine relevant pressures and temperatures for low and high H_2 concentrations. A data gap in 30% vol. to 70% vol. of H_2 has been identified and is scheduled to be filled in 2021.
- Research on Dual-Mode Dual-Fuel combustion using oxymethylene dimethyl ethers (OMEx) as an e-fuel has demonstrated a practical, efficient Low Temperature Combustion (LTC) system with low engine-out NO_x. https://www.sciencedirect.com/science/article/abs/pii/S0016236120308942 .
- Two pre-competitive projects jointly funded by the German Research Association for Combustion Engines (FVV) and the Swiss Federal Office of Energy were successfully completed. One showed the potential of high-pressure direct injection of natural gas in a compression ignition engine, including the potential to

substantially reduce methane slip. The second study led to improved engine heat transfer models, enabling further engine efficiency improvements.

Strengthening collaboration and TCP renewal

- 42nd Task Leaders Meeting (TLM) was held virtually in August 2020. Each Task held virtual workshops prior to the meeting. Task Leaders then presented summaries at the TLM. 45 to 55 participants attended daily.
- System analysis links established with AMF and ETSAP.
- An initiative on an Innovative Training Network for PhD students on the topic of NH_3 as a future non-carbon fuel is being pursued by TCP members.
- Covid-19 caused cancellation of external meetings focused on Combustion TCP activities. (*e.g.*, the Third "Gas Engine Combustion Fundamentals" workshop and the Annual Spray in Combustion Task Workshop.)

Dissemination and publications

- The Combustion TCP submitted two project descriptions to the IEA initiative: "Today in the lab, tomorrow in energy." The TCP's project on transitioning to "H2-rich fuels" was selected by CERT delegates as one of five submissions for promotion in the first round of this IEA initiative and can be found at this link: https://www.iea.org/commentaries/today-in-the-lab-tomorrow-in-energy-2 . The TCP's second submission on Optimization of fuels and engines to boost efficiency and performance was recently published on the IEA website: https://www.iea.org/reports/today-in-the-lab-tomorrow-in-energy .
- The TCP website has been fully updated. TLM presentations are now posted. Public access is now granted to information describing our meetings and presentation/discussion topics.
- TCP visibility in the scientific community continues with extensive technical/scientific publications of TCP research in peer reviewed journals and presentations at conferences.
- Planning is underway for a 2021 IEA/ETH/ERCOFTAC Gas Engine Combustion Fundamentals workshop.
- A review on the influence of additives on combustion of biomass with high content of ash forming species was completed, resulting in a comprehensive review paper in a high-impact journal.

Collaboration and Co-operation

Other IEA network TCPs and co-ordination groups

- **The TCP participated in the December 2020 ETSAP workshop and presented information on the scope and activities of the Combustion TCP overall and the Systems Analysis Task, and the performance of advanced fuels in end-use sectors**. Potential areas of collaboration with ETSAP were discussed.
- **A joint full day workshop was held by the Combustion and Advanced Motor Fuels TCPs to discuss challenges, opportunities and requirements for future combustion systems and advanced fuels**. More than 90 participants attended, including internationally recognized experts from both TCPs, as well as management and R&D representatives from industry, regulatory agencies, and other key stakeholders. Advanced fuels and engines for road transport, shipping, aviation, off-road machinery, and power generation were considered. Several areas of possible new collaboration between both TCPs and industry were identified and will be explored within the TCP's strategic planning processes. (Nov. 2019).
- The TCP provided summary input to TCG Fall meeting.

IEA secretariat

- Presentations and updates on IEA needs and priorities continue by our desk officer at our TCP meetings.
- The TCP provided input to several IEA efforts: a) the ETP2020 on future engine/fuel technologies, including aviation and marine applications; b) the Global Fuel Economy Initiative (GFEI) report; and c) discussions on the compatibility of biofuels and marine engines.
- The TCP reviewed ETP2020 and GEVO 2020 documents and the fuel economy and shipping sections of the Tracking Clean Energy Progress (TCEP) website

Membership

- New participants in the Systems Analysis task are being explored.
- IFPEN in France ended participation in the TCP for internal corporate reasons.

Management

- **Successful virtual ExCo, Strategy and a multi-day Task Leaders Meetings were held** (because of Covid restrictions). The virtual Task Leaders Meeting drew between 45 and 55 participants.

- **A new Systems Analysis (SA) task development effort is proceeding.** The SA task is envisioned to focus on exploiting high level systems analysis tools to analyze and demonstrate the overall system impacts of combustion technology advances and to assist with the development of policy recommendations. 20 to 30 potential task members met online to discuss capabilities, common ground for collaboration, tools and methodologies, and future meetings. The next ExCo meeting will consider approving this new task.
- **The Low Temperature Combustion Task is exploring research direction changes, potentially as a new task.**
- **New tasks are also being explored in two other areas: Hydrogen and Its Vector Fuels (e.g., Ammonia), and Exhaust Aftertreatment**. Each task development effort plans to provide a Task Proposal by next ExCo.

Outlook to the Future

- Outreach to India continued in 2020.

MEETINGS OR WORKSHOPS by the TCP

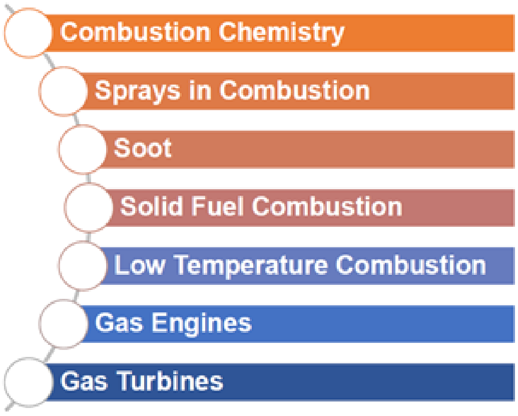
2020 TCP Management Meetings			**2021 TCP Management Meetings**	
Place	*Date*		*Place*	*Date*
Virtual (Strategy)	6/11/20		Paris, France (Strategy)	5/3/21
Virtual (ExCo)	6/12/20		Paris, France (ExCo)	5/4/21
Virtual (ExCo)	8/27/20		Bad Neuenahr, Germany (ExCo)	TBD

TCP ANNEX OR TASK MEETINGS

TCP Annex/Task	**Place**	**Date**
2019 Annual TCP Task Leaders Meeting	Montreux, Switzerland	11/3-7/19
2019 Joint Workshop with the AMF TCP	Montreux, Switzerland	11/6/19
2020 Annual TCP Task Leaders Meeting	Virtual	8/23-26/20
2021 Annual TCP Task Leaders Meeting.	Bad Neuenahr, Germany	TBD

ONGOING ANNEXES

Our research spans from combustion fundamentals to technical applications. See APPEDIX for Task details.



PLANNED ANNEXES (Under discussion)

Name	**Expected Objectives / ey deliverables**	**Launch date**	**Potential Participants**	**Main planned activities (Details TBD)**
Systems Analysis	2021	TBD	TBD	Assess impacts of advanced high-efficiency combustion strategies in a full vehicle/vehicle fleet transportation energy sector context.
Hydrogen and Its Vector Fuels	2021	TBD	TBD	Explore alternatives to carbon-based fuels for various end-use technologies.
Exhaust Aftertreatment	TBD	TBD	TBD	Explore aftertreatment systems in combination with advanced high-efficiency combustion strategies for further engine emissions reductions.

APPENDIX: Current Combustion TCP Task overviews.

Research Area	Date Approved	End date	Participants	Milestones		
				Latest Workshops	Interim results this year	Expected final results
Combustion Chemistry	2014	Tbd*	Finland France Japan Sweden Switzerland USA	Aug. 1-26, 2020 (Virtual)	• Two papers on the low- and high- temperature combustion chemistry of diisobutylene in progress. Diisobutylene is one of six bio-derived fuels with the highest potential efficiency for spark ignition engines and that have the fewest barriers to market.	**Objective**: Predictive chemical kinetic models for renewable fuels and their blends with petroleum fuels to support computational optimization of combustion devices. **Key deliverables**: • Quantitative data on species concentrations, flame speeds, and ignition delay to support the development of chemical kinetic mechanisms. • Identification of important oxidation pathways needed for model development. • Validated kinetic models.
Sprays in Combustion	2014	Tbd*	Finland France Germany Japan Korea Spain Sweden Switzerland USA	Aug. 1-26, 2020 (Virtual)	• Improvements made in near nozzle modeling. • New evaporation and drag model for gasoline injection developed. • More accurate flash boiling predictions being developed. • Spray wall impingement characterization becoming increasingly important (PACE Collaboration, USA). • Fuel film detection shown possible with neutron imaging. • New models of spray/wall impingement are under development.	**Objective:** Develop a fundamental scientific understanding of spray formation and mixing, as well as a concurrent capability for computationally designing fuel and air mixing processes in combustion systems with fuel sprays. **Key deliverables**: • Utilizing both experiments and simulation, develop an understanding of the influence of sprays on advanced combustion strategies that promise clean burning, highly efficient combustion engines. • Conduct experimental measurements and computational simulations on common engine fuel injection cases, such as those promoted by the Engine Combustion Network. Worldwide efforts such as this focus the research community on solving fundamental problems that speed the advancement of fuel injection and spray combustion technologies. • Develop a fundamental understanding of cavitation in fuel injector nozzles, its effect on sprays, and its propensity to damage nozzles over time. • Advance the state-of-the-art of computational simulations of sprays relevant to engine designers.

Research Area	Date Approved	End date	Participants	Milestones		
				Latest Workshops	Interim results this year	Expected final results
Soot	2016	Tbd*	US Japan France Spain Sweden	Aug. 1-26, 2020 (Virtual)	• Published two papers on soot formation processes from fuel injection under diesel-like conditions: 1) https://doi.org/10.3390/app10165460; 2) https://doi.org/10.4271/2020-01-2120 • Published a paper on fuel spray-wall interactions in direct injection gasoline engines https://doi.org/10.1016/j.proci.2020.09.004 • Contributed to the international "Engine Combustion Network" (ECN) collaboration. • Task members are co-authors on a proposed review publication to Progress in Energy and Combustion Science on soot particle formation processes in gasoline direct injection engines. • Developing optical techniques to better understand the connection between liquid fuel films and soot formation in gasoline direct-injection spark ignition engines. This work is also contributing to the database of the ECN collaboration. • Measured PAH formation and growth (high-speed LIF), as well as soot volume fraction (high-speed DBI) for ECN Spray A-3 (a new injector target). • Investigated the pressure effects on soot formation rate via time-resolved measurements of PAH LIF and DBI-EI for soot volume fraction under pyrolysis conditions. • Quantified the effects of aromatics on the PAH and soot formation processes by doping n-dodecane with 1, 2, 3 and 4-ring aromatics under pyrolysis conditions. • Studied soot propensity by measuring the soot onset temperature, formation rate and yield under pyrolysis for various diesel and gasoline surrogates and single-component fuels. • Explored molecular dissociation of fuel into smaller species and the subsequent growth to PAHs under inert environments at high temperatures. • Performed experimental characterization of fuel type on fundamental combustion and soot formation processes under diesel-like conditions. • Conducted experiments to determine lubricating oil impacts on gasoline particulate filter efficiency.	**Objective**: Leverage international collaborations on experiments and modeling toward a foundational scientific under-standing of soot formation/oxidation processes that will enable prediction of soot mass, particle number, and particle structure for a variety of fuels. Expand the current understanding of how soot toxicity and environmental impact change with fuel and combustion concept. **Key deliverables**: • Detailed predictive models describing formation of gas-phase species leading to soot formation, the soot nucleation process, and soot particle oxidation. • Reduced complexity engineering models with sufficient accuracy for design optimization. • Characterize and understand the effects of engine parameters on formation, oxidation, and emissions.

Research Area	Date Approved	End date	Participants	Milestones		
				Latest Workshops	Interim results this year	Expected final results

Solid Fuel Combustion	2016	Tbd*	Germany
			Spain
			Japan
				Aug. 1-26, 2020 (Virtual)	• New pyrolysis model implemented in collaboration with TU Graz (Austria, not member of this TCP)
					• New models on the movement of the solid particles in the bed have been implemented.
					• Joint review paper on additives and their effect on biomass slagging, coauthored by the chairs of the task, has been accepted for publication at a highly cited journal.
					• Effort to include new members in the Task. Possibility of participation by DBFZ – Germany.
						Objective:
						To gain a better understanding of the combustion of solid fuels that is required to develop more flexible, cleaner, and efficient combined heat and power systems.
						Key deliverables:
						• Improved designs of solid-fuel combustors.
						• Advanced models for solid fuel gasifier or combustor pyrolysis and char oxidation that:
						  ○ Incorporate improved chemical kinetic mechanisms accounting for secondary reactions.
						  ○ Include high inorganic content agricultural residues.
						• Advanced process monitoring sensors.

Low Temperature Combustion (LTC)	2014	Tbd*	France Japan Norway South Korea Spain Sweden USA	Aug. 1-26, 2020 (Virtual)	• LTC Task participating countries in Japan, South Korea, Spain, France, Sweden, and USA have shown with different contributions how lean and dilute low-temperature combustion concepts can increase the energy efficiency and decrease exhaust emissions from ICEs. • Low-temperature gasoline compression ignition (LTGC) experiments using Additive Mixing Fuel Injection (AMFI) enables high-efficiency operation over load-speed map with very low NOx and soot. • As a part of US DOE's Co-Optima initiative, drive-cycle modeling of multimode SI engine operation indicates higher fuel economy for fuels with high RON and octane sensitivity. • In the SIP program in Japan, ultra-lean burn SI engine with thermoelectric recovery enabled brake thermal efficiency of 51.5%. • Published improved understanding of spray-wall interactions in direct injection gasoline engines https://doi.org/10.1016/j.proci.2020.09.004	**Objective**: Examine a wide range of LTC engine concepts to gain fundamental understanding of the in-cylinder processes governing efficiency and exhaust-emissions formation, and assess their technical potential for increasing energy efficiency in vehicle applications. **Key deliverables**: • Assessment of the drive-cycle fuel consumption of LTC and advanced spark-ignition combustion systems. • Evaluation of fuel effects on LTC operation and appraisal of the effectiveness of standard fuel quality metrics like octane number metrics. • Evaluation and further development of LTC combustion timing control methodologies. • Further development of LTC by examining different exhaust gas recirculation (EGR) concepts and multiple injection strategies. • Clarification of the connection between local fuel-to-air ratio and ignition.

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<tr><th rowspan="2">Research Area</th><th rowspan="2">Date Approved</th><th rowspan="2">End date</th><th rowspan="2">Participants</th><th colspan="3">Milestones</th></tr>
<tr><th>Latest Workshops</th><th>Interim results this year</th><th>Expected final results</th></tr>
<tr><td>Gas Turbines</td><td>2014</td><td>Tbd*</td><td>France
Switzerland
Japan
UK
Sweden
Norway</td><td>Aug. 1-26, 2020 (Virtual)</td><td>• Recent findings indicate that the level of H_2 in the fuel gas mixture can be up to volumetric shares of 20-30% of H_2 (in special cases up to 50% by volume) without major drawbacks in gas turbine operation and NO_x/CO emission characteristics. This is being further confirmed by additional data generated for H_2 content between 30-70% by volume. Retrofit solutions and new combustion technologies (micro mix technology) are being developed for high H_2 content (beyond 50% H_2).
• Total system solutions for direct combustion of NH_3 (ammonia) either via direct combustion of NH_3 using staged combustion concepts or via decomposition of NH_3 prior to combustion are being investigated. NO_x emissions less than 100 ppm have been achieved.</td><td>Objective:
Develop combustion technologies for high efficiency, ultra-low emission gas turbine engines for power generation/industrial processes/transport (air, sea).
Key deliverables:
• Understanding needed for adoption of low carbon fuels, including the extension of operational limits (flashback, blow-out, maximum load gradients) for:
○ CH_4/H_2 (Methane/Hydrogen) fuel mixtures.
○ H_2-carrier fuels (ammonia, methanol).
• Predictive models for flame instabilities.
• Quantitative species, flow, and temperature measurements supporting design evaluation and model development.</td></tr>
<tr><td>Gas Engines</td><td>2014</td><td>Tbd*</td><td>Finland
France
Germany
Japan
Korea
Spain
Switzerland
USA</td><td>Aug. 1-26, 2020 (Virtual)</td><td>• Paper on NH_3 combustion in SI engines (ProCI 2020 & FUEL 2020)
• Hydrogen/Methane admixtures studied in SI engine for CHP operation (2 papers in IJER 2020)
• Numerous pre-chamber combustion papers: Optical characterization in heavy-duty engine (ProCI 2020), direct numerical simulation (CNF 2020) and development of 3D-CFD (CNF 2019 & IJER 2019) and phenomenological models (CNF 2020 & IJER 2020)
• Dual fuel combustion papers: Characterization in rapid compression expansion machine (ProCI 2020 & FUEL 2019), optical engine (2 papers in APEN 2019 & SAE 2020) and new optical engine (Rostock LEC 2020), development of 3D-CFD (SAE 2019) and phenomenological models (FUEL 2020, CIMAC 2019)
• High-pressure direct injection of methane for CI combustion papers: characterization in optically accessible constant volume chamber (FUEL 2019) and development of 3D-CFD models (CNF 2020 & CNF 2019; IJER 2020 & POF 2019)
• “Walls”: Paper on data-driven approach employed to develop improved CFD heat transfer model using various DNS/high-fidelity simulation datasets (ProCI 2020).
• Knock: In a heavy-duty optical engine, showed that three popular state-of-the-art NG chemical kinetics</td><td>Objective:
Support the development of future ultra-low emission natural gas engine combustion systems with Diesel-like efficiencies suitable for surface transport as well as co-generation/grid balancing.
Key deliverables:
• Optical diagnostics for lean premixed natural gas engine ignition systems (pre-chambers, dual fuel micro-pilots).
• Characterization of non-premixed high-pressure direct injection (HPDI) combustion concepts that offer reduced methane emissions.
• Predictive computational tools for pre-chamber, dual fuel and HPDI combustion for engine optimization.
• Improvement of chemical kinetic models for lean premixed natural gas and bio-derived fuels.
• Improved understanding and models for flame–wall interaction, heat transfer and CH_4/NH_3 slip.
• Identification of factors leading to auto-ignition (knock).</td></tr>
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Research Area	Date Approved	End date	Participants	Milestones		
				Latest Workshops	Interim results this year	Expected final results
					mechanisms predict knock quite well at near-stoichiometric operating conditions, and that proximity of the propagating flame and cylinder walls to the onset of knock had little influence. Developing a specifically designed injector for lube oil addition in view of pre-ignition. Knock free operation with Pme 3.0 MPa was achieved.	

* Note: There are no fixed end dates. Instead, every research area is evaluated at the annual TCP strategy meeting.