EUWP TECHNOLOGY COLLABORATION PROGRAMMES (TCPs)

ANNUAL BRIEFING

TCP NAME	Report Date
Clean and Efficient Combustion (Combustion TCP)	2/25/2020

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 can be made sustainable with continued advancements and low-carbon fuels.

- **Significantly greater light-duty fleet CO_2 reductions can be achieved by promoting higher efficiency hybrid ICE powertrains and renewable drop-in fuels in conjunction with full electrification than can be achieved with electrification alone**.
- **Internal combustion engine (ICE) powered vehicles, including hybrids, will dominate transportation for many decades – continued progress on fuel efficiency and emissions reduction is essential.**
  - The development and large-scale employment of renewable low-CO_2 fuels is required to complement the electrification of parts of the transportation sector.
  - Advanced low-temperature combustion (LTC) has potential to improve light-duty vehicle fuel economy by 20% at a lower cost and result in a smaller fleet CO_2 footprint than electrification alone. Mazda's launch of its SkyActiv-X engine shows that LTC is becoming practical. Fuels with improved octane characteristics offer even higher efficiency potential.
  - For heavy-duty (HD) engine applications, dual-fuel gasoline-diesel engine technologies can provide high diesel-like efficiencies with lower engine-out NOx than diesel alone, offering potential for efficient and clean use of gasoline-like fuels in the HD transportation sector.
- **Existing power generation systems using gas turbines or ICEs are being qualified on higher and higher concentrations of hydrogen (H_2) blended with natural gas to pave a path for early adoption of hydrogen to achieve immediate reduction of greenhouse gas emissions.** These power generation systems provide quick response to electrical load variations and thus play key roles in grid stabilization. All major gas turbine manufacturers have recently announced that H_2 in natural gas can be tolerated at levels up to 20-30% vol. (in single cases up to 50% vol.) without major drawbacks in operating and emissions characteristics. Achieving higher H_2 tolerance by further advancing our understanding will have a major impact on the introduction of H_2 into our energy system.
- The use of H_2-carrier fuels (*e.g.*, ammonia (NH_3), methanol) is 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 in ICEs are currently the main NH_3 applications being considered. When burned directly as NH_3 in conventional combustion systems, the major NH_3 challenges are its low combustion speed and NOx and NH_3 emission compromises. Staged combustion concepts offer a potential remedy for these drawbacks.
- Development of accurate chemical kinetic combustion models for new bio-based fuels and the blends of these fuels with conventional fuels is helping predict the benefits of biofuels. These advanced models are contributing to maximizing combustion efficiency, minimizing pollutant emissions, and reducing the carbon footprint of all combustion devices.

Achievements *(recent developments in the last two years only)*

Scientific focus

- **LTC Task research conducted under the US DOE's Co-Optima fuel initiative concluded its boosted spark-ignition engine research. The results isolated fuel properties that promote higher light-duty vehicle fuel economy for gasoline-like fuels, including the identification of ten biofuel blendstocks that can provide those properties.**
- The combustion characteristics of methane-H_2 blends have been clarified at gas turbine relevant pressures and temperatures for the full range of H_2 concentrations (0 to 100%).

- NOx emissions have been significantly reduced (less than 100 ppm) for direct combustion of ammonia (NH_3) via staged gas turbine combustion.

Strengthening collaboration and TCP renewal

- 41st Task Leaders Meeting (TLM) was held in November in Switzerland with more than 40 presentations and substantial discussions among TLM researchers and industry participants.
- **A highly successful technical session was held at the TLM to explore Systems Analysis as a task. The TCP agreed to continue developing this task with one goal being to provide policy guidance regarding advanced clean and efficient combustion technologies.** (Nov. 2019)
- An exploratory session was held at the TLM to consider Exhaust Aftertreatment as a task. Discussions about integrating this topic into the TCP are ongoing. (Nov. 2019)
- A new Soot Task Leader, Will Northrop (Univ. of Minnesota, USA), was endorsed by the task.

Dissemination and publications

- The annual Spray in Combustion Task workshop held at the SAE World Congress. (April 2019)
- TCP visibility in the scientific community continues with extensive technical/scientific publications of TCP research in peer reviewed journals and presentations at conferences.
- The LTC Task contributed to two major publications conducted under the US DOE's Co-Optima fuel initiative: (a) Co-Optimization of Fuels & Engines: Efficiency Merit Function for Spark-Ignition Engines; Revisions and Improvements Based on FY16-17 Research and (b) Ten Blendstocks Derived From Biomass For Turbocharged Spark Ignition Engines: Bio-blendstocks With Potential for Highest Engine Efficiency.
- TCP webpage redesign and renewal are ongoing. TLM presentations are now posted for TCP participant access. Public access is now granted to information describing the nature of the meetings and the titles of presentations and discussion topics.

Collaboration and Co-operation

Other IEA network TCPs and coordinating groups

- **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**. There were more than 90 participants, including internationally recognized experts from both TCPs, and 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 is actively promoting external collaboration as evidenced by the formation of the CONVERGE Working group on soot and the addition of a new topic on spray-wall impingement and combustion to our collaboration with the Engine Combustion Network.
- Funding is being sought to enable continued collaboration with AMF TCP Annex 57 on heavy-duty vehicles. The collaboration is targeting improved fuel efficiency and the concurrent CO_2 benefits from advanced combustion technologies using real-world data.
- The TCP participated in the Universal TCP meeting and provided input to TCG Fall meeting.

IEA secretariat

- IEA updates and needs presentations continue by our desk officer at our TCP meetings.
- TCP provided input on future engine/fuel technologies to the ETP2020, including aviation and marine applications. In addition, TCP input was provided to the GFEI.

Membership

- Work continues with IEA legal to update official TCP membership records, such as the recent clarification of the Contracting Parties (CPs) for Germany and Japan.
- Outreach to India continues – Indian guest at our 2019 TLM.

Management

- The second annual TCP strategy workshop was held for planning directions and continued renewal of the Combustion TCP (May 2019).
- Documents for “Roles and Responsibilities” of TCP officers and Task Leaders, “Ground rules for TCP Meetings”, and guidance on acknowledgements of the TCP in publications and presentations were approved and adopted.

Confidential information

Please treat all information wrt potential new members as confidential within the TCP / the EUWP.

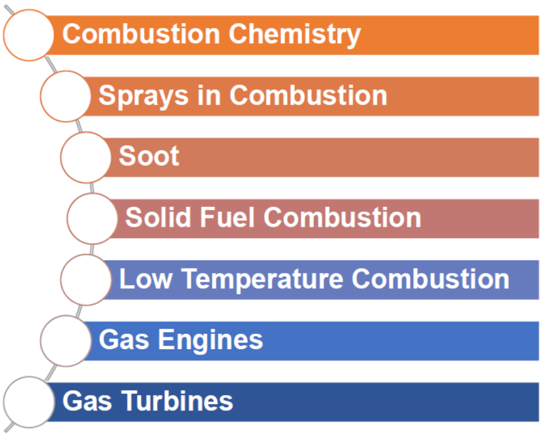
Meetings or Workshops hosted (2019) and planned (2020) by the TCP

2019 TCP Management Meetings		2020 TCP Management Meetings	
Place	*Date*	*Place*	*Date*
Paris, France (Strategy)	5/13/19	Paris, France (Strategy)	3/30/20
Paris, France (ExCo)	5/14/19	Paris, France (ExCo)	3/31/20
Montreux, Switzerland (ExCo)	11/7/19	Bad Neuenahr, Germany (ExCo)	8/27/20

TCP meetings to advance our scientific work	*Place*	*Date*
2019 Annual TCP Task Leaders Meeting with sessions for each task/research area to discuss research progress.	Montreux, Switzerland	11/3-7/19
2019 Joint Workshop with the AMF TCP	Montreux, Switzerland	11/6/19
2020 Annual TCP Task Leaders Meeting with sessions for each task/research area to discuss research progress.	Bad Neuenahr, Germany	8/23-27/20

Current RESEARCH AREAS

Our research spans from combustion fundamentals to technical applications



(See tables in the following pages in the Appendix for details on each task.)

Potential new RESEARCH AREAS

Research Area	Expected start date	Expected end date	Collaboration	Technology Policy Message
Systems Analysis (Being developed as a stand-alone task)	2020	TBD	TBD	Assessing the impact of advanced high-efficiency combustion strategies in a broader vehicle context. Details TBD.
Exhaust Aftertreatment (In scouting stage)	TBD	TBD	TBD	Exploring engine exhaust aftertreatment systems for further reduction of emissions from engines employing advanced high-efficiency combustion strategies. Details TBD.

APPENDIX: Current Combustion TCP Task overviews.

Research Area	Date Approved	End date	Participants	Milestones		
				Latest Workshops	Interim results so far	Expected final results
Combustion Chemistry	2014	Tbd*	Finland France Japan Sweden Switzerland USA	Nov. 3-7, 2019	• Developed fundamental experimental datasets and a preliminary chemical kinetic model for di-isobutylene, a biomass-derived fuel with high Research Octane Number (RON) and octane sensitivity (S) for high-efficiency down-sized boosted spark-ignition and multi-mode engines.	**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	Nov. 3-7, 2019	• Spray research in several groups around the world are focusing on the challenging problem of sprays impinging on engine walls. Improved understanding of this phenomenon promises to reduce soot emissions from engines while improving efficiency • Computational simulation tools available to engine designers showed significant improvements in 2019. Improvements to spray models include improved flash-boiling evaporation models and the incorporation of manufacturing variability between injector holes. These more accurate simulation tools will increase the overall predictive capabilities of spray and engine simulations • The gas engine pilot fuel ignition process has been studied by detailed computational methods. Radically new findings on the chemistry between the diesel pilot and the methane-air mixture has been discovered. For example, it was revealed that the pilot fuel injection duration has a strong impact on the reliable ignition of the methane-air mixture.	**Objective:** Develop a foundational scientific understanding of spray formation and mixing and 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 so far	Expected final results
Soot	2016	Tbd*	US Japan France Spain Sweden	Nov. 3-7, 2019	• A new Soot Task Leader – Will Northrop – volunteered to take the reins and was endorsed by the other participants in the soot task. • TCP discussions at the last TLM on GDI films helped differentiate soot production from pool fires from production due to pyrolysis – resulting in a focusing of Task Participant efforts • Task work provided independent verification from international members that soot from fuel films controls soot formation and that soot from fuel films in GDI engines seems to be more significant than soot from air/fuel mixing. Fuel films include both piston top and injector tip (leading to fouling and increased PM/PN emissions). • A reference case for soot measurements and modeling was defined within a collaboration effort (CONVERGE Working group on soot)	**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.
Solid Fuel Combustion	2016	Tbd*	Germany Spain Japan	Nov. 3-7, 2019	• After the last TLM, a new task member from Switzerland has joined the group • The solid fuel combustion model is now able to model systems in the MW range. • New research groups have joined the community to develop the combustion model.	**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.

Research Area	Date Approved	End date	Participants	Milestones		
				Latest Workshops	Interim results so far	Expected final results
Low Temperature Combustion (LTC)	2014	Tbd*	France Japan Norway South Korea Spain Sweden USA	Nov. 3-7, 2019	• Experiments and modeling have shown that the octane requirement of mixed-mode combustion (SPCCI/SACI) is the same as for conventional stoichiometric, boosted, SI engines, with fuels of higher RON and S providing higher loads. Hence, the thermal efficiency of a multimode engine with SACI will benefit strongly from increasing RON and S, but only if the compression ratio is increased. • For beyond-Motored Octane Number (MON) conditions, HCCI and LTGC experiments show a generally poor performance of Octane Index for fuel components such as olefins and aromatics. • For lean stratified spark-ignition operation, in-cylinder diagnostics suggest that the current PMI sooting metric needs to be enhanced to take fuel oxygenation into account and possibly de-emphasize the importance of volatility. • For LTC concepts, the effect of ozone on autoignition can be strong. It has been shown that ozone enhances LTHR in HCCI engine and that a few ppm advances HCCI autoignition timing for all tested fuels. However, the presence of NO can complicate control schemes since $NO + O_3 = NO_2 + O_2$ leads to retard of autoignition timing. • PPC operation has been expanded to very low cetane number using methanol, showing higher efficiency than for diesel or gasoline fuels. • For RCCI, progress was made towards 6-cylinder demonstration with diesel and gasoline using a Volvo MD8 engine. Diesel efficiency can be maintained while meeting NO_x regulations without SCR, but HC and CO are a challenge, especially during cold starts. • In the SIP lean burn project in Japan, +50% BTE was demonstrated with a lean-burn engine. Increased turbulence was required for fast combustion, and further benefits were demonstrated with high flame-speed fuels.	**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 so far</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>Nov. 3-7, 2019</td><td>• Recent findings indicate that the level of H_2 (hydrogen) in the fuel gas mixture can be up to volumetric shares of 20-30% by volume H_2 (in special cases up to 50% by volume) without major drawbacks in gas turbine operation and NOx/CO emission characteristics.
• NOx emission is significantly reduced for direct combustion of NH_3 (ammonia) when using staged combustion concepts. NOx emissions less than 100ppm 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>Nov. 3-7, 2019</td><td>• For premixed, prechamber gas engines, the lean limit can be extended significantly by using scavenged pre-chambers. Improved understanding of many aspects was achieved, including confided flow, high-speed jets, auto-ignition and/or turbulent premixed energy conversion, and flame/wall interaction. Optical test rigs, Direct Numerical Simulation, RANS and LES were combined to developing a prototype passenger-car size pre-chamber as part of the EU “GasON” project, where a demonstrator vehicle was built.
• For unscavenged prechamber lean-burn engines, advances were achieved by combining simulations and experiments in a Rapid Compression Expansion Machine and in metal engines. The advancements enabled the development of a CFD simulation and phenomenological models useable for engine optimization.
• Novel low temperature plasma ignition system has been applied to a GHP engine.
• For dual fuel gas engines ignited by means of micro pilots, experiments in Rapid Compression Machines and optical engines have been performed. The combination of numerical simulations and experiments has improved</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 so far	Expected final results
					the understanding of the impact of methane addition to the oxidizer on the pilot auto-ignition event, the sooting propensity of the pilot spray as well as the injection duration. Alternative fuels (PODME) for the pilot spray were also studied. The advances have helped in the development numerical tools for engine design. • High-pressure direct injection of methane/natural gas with mixing controlled combustion is gaining momentum due to significant advantages in terms methane slip. Real-gas effects must however be accounted for due the nature of the under expanded jet. The needle dynamics were found to depend on the pressure ratio and level, and strongly impact spray penetration. Potential soot formation and NOx in such engines can be readily addressed with appropriate aftertreatment. • Catalytic conversion of engine-out methane continues to be a considerable challenge due to the low reactivity of CH4 and the ultra-low temperatures at lean operation. • Concerning wall heat transfer in engines, significant advances have been made thanks to fully resolved data of velocity and thermal boundary layers using a combination of LES, DNS and optical experiments in pent-roof engines. The first ever high-order LES (filtered DNS) with moving valves was performed for the TCC-III engine. For more canonical configurations, wall models have been developed using DNS. • NH_3 combustion with various levels of hydrogen addition and in combination with supercharging was studied in a modern GDI SI engine. It was seen that satisfactory efficiency can be achieved. However, a compromise must be found between engine out NOx or NH_3 emission. In addition, the auto-ignition kinetics of NH_3 play an important role while hydrogen acts as an ignition and combustion promoter. And last, the turbulence flame interaction also needs to be studied for developing an accurate ICE flame propagation model.	

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