TECHNOLOGY COLLABORATION PROGRAMME (TCP)
EUWP ANNUAL BRIEFING

TCP NAME	Report Date
Clean and Efficient Combustion (Combustion TCP)	2/15/2022

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 technology advancements and fuel de-carbonization. Advanced combustion technologies offer pathways to zero carbon, carbon neutral, and reduced carbon emissions technologies for all the major energy sectors. Continued progress in reducing pollutant emissions such as particulates, oxides of nitrogen, and unburned hydrocarbons will be necessary to address urban health and social justice concerns.

- Progress in the Internal Combustion Engine (ICE) technologies and accelerated production of renewable fuels are especially important for hard-to-abate transport sectors such as heavy-duty on/off road, aviation, and marine. Moreover, while considering the current rapid electrification of light-duty transportation, in 2040 there still will be over one billion ICE powered LDVs worldwide needing low-carbon drop-in fuels.
- Development and advancement of the fuel dedicated engines (for hydrogen, ammonia, methanol) are crucial for realistic and effective decarbonization of the energy sector while maintaining energy security.
- An admission of up to 30% by volume of H_2 into the public natural gas grid for CO_2 reduction is now commonly accepted as feasible in most countries and causes no (major) issue with various end-use sectors (industry, power generation, households). Combustion TCP generated data supports this conclusion.
- Use of ammonia as a fuel can eliminate tail-pipe CO_2 emissions, or when combined with other fuels, significantly reduce them. Large consortia (led by MAN, Wartsila, IHI, J-Eng (Japan) and others) have embarked on the development of ammonia-fueled engines for the marine sector. Korea and Japan have started ambitious programs to demonstrate the use of co-fired ammonia-coal furnace/boiler units.

Achievements

- Coupled fundamental advanced combustion research results to policy recommendations through vehicle level systems analysis. Demonstrated 20% fuel economy improvement over diesel in a US Class 6 delivery application with advanced combustion.
- Three new tasks (annexes) were initiated in 2021: a) System Analysis, b) Hydrogen and Its Vector Fuels (HVF), and c) net-Zero Carbon Engine Technology (n-ZCET). The new tasks respond to needs to develop new technologies to reduce carbon emissions, improve our understanding of which technologies will best serve the global need to reduce carbon emissions, and provide policy recommendations.
- The Low Temperature Combustion (LTC) task was successfully completed. This task provided significant new understanding about high-efficiency LTC combustion concepts and improved engine design models.
- Combined drive-cycle and combustion modeling revealed that advanced LTC combustion can be synergistically implemented in a power-split hybrid electrical vehicle, providing additional fuel-economy gains compared to a hybrid with only conventional stoichiometric SI combustion.

Dissemination and publications

- The project "Combining Low Temperature Combustion and Low Carbon E-fuels or Bio-fuels for Cleaner and More Efficient Transportation" was submitted and accepted for the "Today in the Lab, Tomorrow in Energy" initiative. This project aims at evaluating the prospects of attaining high efficiency, ultra-low emissions of nitrogen oxides and soot, and carbon footprint reduction when combining LTC concepts with renewable, low-carbon fuels produced from either bio-sources or excess renewable electricity.
- TCP visibility in the scientific community continues with extensive technical/scientific publications of TCP research in peer reviewed journals and presentations at conferences.
- LTC research conducted as part of the US DOE's Co-optimization of Fuels and Engines project was included in several recent major DOE Capstone Webinars. The main findings of the project were summarized.

Collaboration and Co-operation

Other IEA network TCPs and co-ordination groups

- The Combustion TCP in collaboration with the AMF TCP, and the H2 TCP, have proposed a lifecycle analysis of hydrogen-fueled ICEs for the IEA GREET+ Extension Project. The Combustion TCP focus is on

- improving efficiency and refining load speed maps, as well as minimizing precious metal use in the aftertreatment system. The collaboration was further explored at a December 16, 2021 meeting.
- The Combustion and ETSAP TCPs have proposed a joint project titled "Modelling of Advanced Combustion Technology & Joint Workshops". The collaboration is to be focused on the system level characterization of renewable fuel technologies (biofuels, E-fuels, NH_3, and H_2) utilized in transport and energy production sectors. The collaboration was explored in an August 2021 workshop.
- The Combustion TCP takes part in AMF TCP annex 60 related to marine fuels.
- Participated with other TCPS in the TCP Sectoral Group Discussion on E-fuels.
- TCP current highlights presented at the March EUWP and November TCG meetings.
- Initial discussions occurred with the H2 TCP to explore a Joint Workshop on "Hydrogen combustion for electricity: Hydrogen gas turbines" for 2022. Further discussion anticipated.

IEA secretariat

- The TCP participated in the review of the IEA Global Fuel Economy Initiative Benchmarking Report
- Presentations and updates on IEA needs and priorities continue by our desk officer at our TCP meetings.

Membership

- New EU partners (Netherlands and Italy) and India are being discussed/explored.

Management

- Exhaust aftertreatment for advanced high-efficiency, low-carbon emission engines is being considered as a task. This task could provide an essential research complement to existing Combustion TCP activities.
- Successful ExCo (2) and Strategy meetings were held virtually.
- 43rd Task Leaders Meeting (TLM), hosted by Germany, was held virtually in September 2021. Each task held virtual workshops prior to the meeting. Task Leaders then presented summaries at the TLM. More than 40 researchers and program managers attended daily from the 11 member countries.

Outlook to the Future

- Future research in the transportation area is shifting emphasis 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.
- Emphasis is also increasing on optimized use of sustainable fuels – E-Fuels, ammonia, hydrogen, biofuels dimethyl ether, (poly) oxymethylene ethers, and others for all combustion technologies.
- Planned external meetings involving TCP: Ammonia Combustion (Feb. 10, 2022); 1st Symposium on Ammonia Energy (Sept. 1-2 2022 (Cardiff)); and the Annual Spray Workshop (April 4, 2022).

MEETINGS OR WORKSHOPS

2021 TCP Management Meetings			**2022 TCP Management Meetings**	
Place	*Date*		*Place*	*Date*
Virtual (Strategy)	5/3/21		Berlin, Germany (Strategy) (or virtual)	4/25/22
Virtual (ExCo)	5/4/21		Berlin, Germany (ExCo) (or virtual)	4/26/22
Virtual (ExCo)	9/23/21		Sendai, Japan (ExCo) (or virtual)	8/4/22
H2 Project Workshop for Greet+	11/16/21			

FUTURE ANNEX OR TASK MEETINGS

TCP Annex/Task	**Place**	**Date**
2022 Annual TCP Task Leaders Meeting	Sendai, Japan (or virtual)	7/31/22-8/4/22

ANNEXES (See APPENDIX for summaries on each annex)

- The Low Temperature Combustion annex was completed and closed.
- Three new annexes were initiated: (1) Systems Analysis, (2) Hydrogen and Its Vector Fuels (HVFs), and (3) Net-Zero, Carbon Engine Technology (n-ZCET).
- Six current annexes continue: (1) Gas Engines, (2) Gas Turbines, (3) Soot, (4) Sprays in Combustion, (5) Solid Fuel Combustion, and (6) Combustion Chemistry
- A new Exhaust Aftertreatment annex is under consideration.

APPENDIX – Brief summary of Closed, Ongoing and Planned Annexes

CLOSED ANNEXES

Name	Objectives / Key deliverables	Launch /end dates	Participants	Key learnings
Low Temperature Combustion (LTC)	**Objectives:** Explore and assess LTC engine concepts for ICEs with potential for increasing fuel efficiency in vehicles. **Key Deliverables:** Provide knowledgebase on in-cylinder processes governing efficiency and pollutant formation for enabling efficient clean engines.	2014 /2021	France Japan Norway South Korea Spain Sweden USA	• Showed how lean and dilute low-temperature combustion concepts can increase fuel efficiency, thereby lower GHGs, and decrease emissions. • Contributed to the knowledge base required for designing LTC engines. • Documented the important role of fuel properties for achieving optimal benefits of LTC combustion.

ONGOING ANNEXES

Name	Objectives / Key deliverables	Launch /end dates	Participants	Key learnings (Last year)
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.	(New) 2021 /TBD	Finland France Germany Japan Korea Norway Sweden Spain Switzerland USA	• The Combustion TCP and ETSAP TCP have proposed a collaborative project titled "Modelling of Advanced Combustion Technology & Joint Workshops with Combustion TCP" focused on the system level characterization of renewable fuel technologies utilized in transportation sector and energy production. • Taking part in AMF TCP Annex 60 related to marine fuels.
Hydrogen and Its Vector Fuels (HVFs)	**Objectives:** Research hydrogen and its vector non-carbon fuels (e.g., ammonia) for end-use combustion technologies. **Key Deliverables:** Expanded knowledgebase on non-carbon HVF utilization required to develop efficient, clean end-use HVF combustion technologies.	(New) 2021 /TBD	UK Others TBD	• Research has demonstrated the ability to stably combust ammonia, with the addition of small amounts of hydrogen, and to achieve low NOx emission combustion at high pressures relevant to real systems. • A small-scale prototype ICE power generation system was demon-strated. This work also indicates that application in stationary gas turbines for power generation is feasible.
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.	(New) 2021 /TBD	France Japan Spain USA	• Fuels with up to 100% renewable content were successfully examined in a light-duty diesel engine. The results revealed trade-offs between fuel consumption, NOx and PM emissions that depended on blend ratio, load, and engine calibration. • Gasoline-range fuels with <65% renewable content were tested under stoichiometric conditions in a light-duty DISI engine. The knock limits were as expected based on RON and MON, but exceptions were encountered for >30% renewable fractions and for fuels designed to provide high phi-sensitivity.

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	• Research on ignition systems continued for a variety of fuels and ICE combustion systems. • Research into ammonia, H_2, natural gas is expanding as efforts to reduce carbon emissions and to decarbonized fuels grow. • Zoom meeting series established between Combustion TCP partners on pre-chamber engines.
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 Switzerland Japan UK Sweden Norway	• Recent findings confirm that the level of H_2 in the fuel gas mixture can be up to 20-30% by volume (in special cases up to 50% by volume) without major drawbacks in gas turbine operation and NOx/CO emission characteristics. Research has also provided a better understanding of the inception of undesired flashback. Retrofit solutions and new combustion technologies (micro mix technology) are being developed and tested for high H_2 content (beyond 50% H_2). • Total system solutions for direct combustion of NH_3 (ammonia) either via combustion of NH_3 using staged combustion concepts or via decomposition of NH_3 to H_2 prior to combustion are being investigated. NOx emissions less than 100 ppm can be achieved (in most cases using requiring exhaust DeNOx-SCR).
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 detailed formation processes. **b)** Engineering soot models that are sufficiently accurate for combustion system design optimization. **c)** Characterization of the effects of engine parameters on soot formation, oxidation, and emissions.	2014 /TBD	US Japan France Spain Sweden	• Developed experimental imaging techniques for characterizing soot formed from liquid films. • Began research on soot generated by aircraft engines including combust-ion optimization and fuel character-istics for mitigating soot emissions. • Conducted experiments to determine lubricating oil impacts on gasoline particulate filter efficiency. • Completed two-dimensional surface temperature measurements of fuel spray impingement, film formation/evaporation and resulting soot production under gasoline engine cold-start conditions. • Experiments with alternative oxymethylene dimethyl ether fuel produced no soot emissions. • Gas turbine soot modeling was advanced using an improved kinetic mechanism from the Computational Chemistry Consortium and an improved sectional model.

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	• On-line spray workshop held on April 12th, 2021 with over 40 participants and 9 presentations. • Research is shifting emphasis toward renewable fuels, biofuels, H_2 and natural gas.
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 Deliverables: 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	• Showed improved model predictions of temperature (both bed and gas phase), char layer thickness, and volatiles release by a standalone combustion model applied to commercial combustion systems upon implementation of more detailed biomass pyrolysis and char conversion mechanisms. • Showed improved prediction of solid bed movements, shape, and size after implementation of more detailed bed physics in a standalone combustion model, applicability to any type of grate firing systems. • Showed improved combustion behavior of low-grade biomass with the addition of additives, resulting in lower slagging and fouling, and lower activation energy.
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	• Two papers published on the low- and high-temperature combustion chemistry of diisobutylene (DIB). 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. • Combustion chemistry research into continues in a number of areas relevant to zero carbon, renewable and low carbon fuels.

PLANNED ANNEXES

Name	Expected objectives / Key deliverables	Launch date	Potential Participants	Main planned activities (Details TBD)
Exhaust Aftertreatment	**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.