**Research Campaign:** **Combustion under Trans-Critical Conditions**

A White Paper for a ‘Research Campaign’ submitted to the

Decadal Survey on Biological and Physical Sciences Research In Space, 2023 - 2032

**Full Abstract**

Opportunities, needs and potential transformational impacts of research on combustion under trans-critical conditions are presented. The existing state-of-the-art is discussed and complications associated with experiments at one g are reviewed, with many of such complications mitigated in zero g. However, once trans-critical conditions are attained, it may take minutes to hours to reach an equilibrated state. Hence, this white paper presents a general set of recommendations, including the creation of a new high-pressure, high-temperature facility for long duration flight experiments. In addition, specific blends of molecules are suggested due to their unique physical properties with the hope of developing mixing rules for hydrocarbon blends. Critical and trans-critical properties of both conventional and sustainable alternate fuels need to be assessed, as components for gas turbines and diesel engines designed based on fuel properties and empirical behavior of petroleum fuels may not be appropriate for some synthetic fuels. In addition, results and models from research in the trans-critical regime may assist development of new concepts related to the application of endothermic fuels for hypersonic flight, such as for scramjets. The document also cites needs for work under non-reacting conditions and hence may complement interests in the fluid physics arena. There are direct applications to chemical processing, CO2 sequestration, petroleum processing, and refrigeration cycles, as well. In addition, the high temperature/pressure facility and accompanying diagnostics could become available for other types of combustion experiments under otherwise challenging conditions.

Because of the new, complex facility, as well as recommendations for companion experiments at one g and accompanying theoretical modeling, it is presumed that this proposed effort represents a ‘campaign’. However, some costs should be borne by other agencies and international partners. To promote such interactions, encouraging discussions have been held with AFOSR and NASA (GRC), given their interests in rocket engines and aircraft combustors. In addition, interests and coordination from DoE, and probably other DoD agencies, are expected given extreme fuel injection conditions in advanced diesel engines.

Should the proposed facility and capabilities be assembled and the research performed, this work will fit well into the goals of NASA’s Division of Biological and Physical Sciences on being a pioneer characterized by (1) BPS being first or among the first at a frontier, (2) other organizations follow, and (3) BPS collaboration with other organizations. In addition, this research on trans-critical conditions fits into the strategy of BPS by researching processes far from equilibrium, both in physical and chemical terms.

**Combustion under Trans-Critical Conditions**

A White Paper for a ‘Campaign’ submitted to the

Decadal Survey on Biological and Physical Sciences Research In Space, 2023 - 2032

Co-Authors/Endorsements:

Co-Authors

**Dr. Meredith Colket**

Combustion Consulting Services, LLC

36 Gatewood, Avon CT 06001

[med@colket.org](mailto:med@colket.org)

860-748-6612

**Dr. Malissa Lightfoot**

Air Force Research Laboratory

Edwards AFB, CA

**Professor Suresh Aggarwal**

University of Illinois, Chicago

Chicago, IL

**Professor Henry Curran**,

National University of Ireland

Galway, Ireland

**Dr. Scott Goldsborough**,

Argonne National Laboratory

Chicago, IL

**Professor Hai Wang**

Stanford University,

Stanford, CA

**Professor Richard Yetter**

Pennsylvania State University

University Park, PA

Endorsements:

Dr. Michael Hicks, NASA Glenn Research Center

Professor Vedha Nayagam, Case Western Reserve University

Professor Uday Hegde, Case Western Reserve University

Dr. James T. Edwards, Retired Air Force Research Laboratories

Professor Forman Williams, University of California, San Diego

Professor Vigor Yang, Georgia Institute of Technology

Professor William Sirignano, University of California, Irvine

Professor Joseph Oefelein, Georgia Institute of Technology

Professor Timothy Lieuwen, Georgia Institute of Technology

Dr. Mark McLinden, National Institute of Standards and Technology

Dr. Greg Linteris, National Institute of Standards and Technology

Professor Chris Depcik, University of Kansas

Dr. Subramanian Sankaranarayanan, Argonne National Laboratories

Professor Ken Brezinsky, Univ of Illinois, Chicago

Dr. Keith McManus, General Electric Global Research Center

Dr. Joseph Zelina, General Electric Aviation

Dr. Jeff Cohen, Raytheon Technologies Research Center

Dr. Lance Smith, Raytheon Technologies Research Center

Dr. Lyle Pickett, Sandia National Laboratories

Professor Mark Linne, University of Edinburgh

Professor Judith Harrison, Naval Academy

Dr. Sibendu Som, Argonne National Laboratori

**Opportunities for Transformational Research**

Over the past 10-20 years, engineers have been depending on increasingly-useful physics-based modeling tools for the initial design of new propulsion and engine concepts. To mitigate the impact on climate change as well as to create economic benefits of increased energy and propulsion efficiencies, engines with higher operating pressures are desired. These objectives push operating conditions into the trans-critical and supercritical regimes for which physics-based models for multi-component fluids are much less known, starting with the equation-of-state for the required *p*-*V*-*T-γ* relationship. Furthermore, significant non-linearities exist amongst many of the physical properties, and in the trans-critical region, it takes noticeable time to achieve fully equilibrated conditions. A campaign focused on measuring properties of multicomponent (combustion-related) fluids as well as studying combustion phenomena in these regions along with companion model development efforts will create a new paradigm for engineering modeling of trans-critical phenomena and combustion. These new tools will be useful for the design of new high efficiency propulsion and engine systems operating at elevated pressures and temperatures.

**Current State-of-the-Art and Knowledge Gaps**

Two-phase processes at subcritical conditions are relatively well understood, and theories and fairly accurate models are available to simulate these processes. However, there are noticeable gaps both in the fundamental understanding of fluid physics and reaction kinetics under trans-critical/supercritical conditions and in associated modeling capabilities. Maximizing thermodynamic efficiency requires operation at increasingly higher pressures, in many cases, exceeding the critical pressure of many or all of the reactants. In such systems, the temperature of the incoming reactants may be below the critical temperature. But, *as the reactants enter the combustion chamber and undergo heating and mixing processes, they can pass from a subcritical state to a supercritical state. Such a process is defined here as a trans-critical process.* The breadth of this region (in thermodynamic space) can be wide, especially for multi-component mixtures and hence can impact spatio-temporal evaluations of local fluid physical properties, along with ensuing predictions of combustion and fluid dynamics.

Currently, the thermodynamic, transport, and chemical properties of multicomponent fluids under advanced power cycle conditions are not well understood. This gap in understanding is especially wide under nonequilibrium conditions and for trans-critical processes. Development of robust theories and models to represent trans-critical processes accurately has been challenging. Experiments [1, 2] show that the two-phase system transitions from a sharp interface that supports atomization and droplet formation (under subcritical conditions) to a diffusion dominated dense-fluid (thick) mixing layer under trans-critical conditions. The design and execution of experiments seeking to understand this transition are challenging and often complicated by gravitational forces. During combustion the mixture composition and temperature vary temporally and spatially, and are generally difficult to measure locally. Yet, these local fluid conditions define the thermodynamic state in a trans-critical process, although it can take time to attain such a state. Even if the local fluid conditions can be characterized, the determination of the thermodynamic state can be challenging especially for multicomponent reactive mixtures: the critical properties of the mixture are often neither directly nor easily derived from the critical properties of the individual species [3]. At or near the critical point, property anomalies have been observed, including singularities in specific heat and compressibility [4] and complex pressure, temperature dependencies in diffusivity and viscosity [5], phase-separation of dissimilar mixtures and the occurrence of multiple Widom lines [6]. These behaviors can impact mixing and fuel combustion and hinder prediction of these processes.

Theoretical and computational research has led to improved understanding and modeling of interphase dynamics under trans-critical conditions [7-10], including the development of semi-empirical models to account for thermodynamic and transport anomalies for relatively simple fluids and mixtures, and evaluating some multi-component mixture properties. Currently, however, a fundamental understanding of trans-critical processes is still lacking, especially for conditions near the critical point and for the multi-component mixtures inherent to combustion.

The computation of real fluid properties, including the pressure-volume-temperature (p-V-T-γ) behavior of multi-component mixtures, and phase equilibrium are frequently based on the cubic equation of state (EOS), such as the Peng-Robinson equation [11], or the more advanced Benedict-Webb-Rubin (BWR) EOS along with non-linear mixing rules. While these models are useful in many situations, including the supercritical regime, they fundamentally fail to capture the functional behavior near the critical point [12]. Approaches exist for computing thermodynamic properties, such as enthalpy and specific heat, as discussed by Oefelein et al. [13]. Estimates for other properties can also be generated. For example, the respective component properties are combined at a given temperature using the Principle of Corresponding States to obtain the mixture state at a given reference pressure. A pressure correction is then applied using departure functions (e.g., Reid et al. [14]) and chemical potentials and fugacity coefficients are obtained similarly. Viscosity and thermal conductivity are determined using extended corresponding states (Ely and Hanley [15]). Finally, the mass and thermal diffusion coefficients are obtained using methods reported by Bird et al. [16] and Hirschfelder et al. [17] in conjunction with the Corresponding States methodology of Takahashi [18].

These approaches, however, rely on a number of questionable assumptions that may not be valid in the trans-critical regime. The two most critical assumptions are that mean-field thermodynamics and equilibrium are maintained throughout the fluid domain (or that deviations from them are not impactful). However, if the trans-critical trajectory results in the mixture being near the critical point, anomalies in thermodynamic and transport properties alter their underlying functional forms so that mean-field descriptions are not expected to be accurate [4, 5, 12]. This discrepancy can alter predictions of mixing processes and chemical transformations which can affect combustion dynamics, as well as other performance characteristics. Despite such concerns, near-critical models, for example, the so-called “cross over equations of state” (e.g., [19]) have been developed, but they remain untested for the complex mixtures pertinent to combustion, in large part due to the lack of experimental data for comparison. Additionally, the time scales for reaching various equilibrium states, including thermodynamic equilibrium, increase in the trans-critical regime. These time scales remain largely unknown. While semi-empirical approaches have yielded fairly good predictions for single-component fluids, reliable theories and predictive capabilities are needed for multi-component mixtures starting from bi-component mixtures.

For reacting mixtures, detailed kinetic mechanisms have been developed for the oxidation of a variety of hydrocarbons and other fuels. For some fuels at high-pressure conditions, these mechanisms have also been validated against measurements of laminar flame speeds at elevated pressures [20]. NASA researchers have employed detailed mechanisms to examine the droplet ignition and combustion behavior under microgravity conditions, and identified three-stage burning behavior, consisting of ‘hot flame’, ‘warm flame’ and ‘cool flame’ regimes, at elevated pressures [21]. However, these explorations remain substantially below the critical pressures. As the critical point is approached, transient clusters form at the nano scale [22, 23]. Such structures alter local collision rates and temperature definitions, and caging effects due to clusters can result in diffusion-controlled reaction rates [24]. Cluster structures may also alter species profiles near an interface and are responsible for property anomalies discussed earlier, all of which may impact mixing and alter overall combustion behaviors. Finally, time constants associated with relaxation to thermodynamic equilibrium conditions may be of the same order or slower than reaction rate time scales, further complicating interpretations. Research on reacting systems needs to be extended to higher pressures, including examination of multi-stage burning phenomenon at trans-critical conditions for a variety of fuels, including bi-/multi-component mixtures.

The trans-critical regime of hydrocarbons and their mixtures also offers exciting possibilities for a range of new, coupled transport/reaction phenomena not previously understood. This is especially true for multicomponent hydrocarbon fuels for which the criticality is poorly understood at both the molecular and continuum levels. New fluid behaviors and hence, new modes of combustion may be identified at these extreme conditions never studied previously. In the supercritical regime, single and multicomponent fluids are homogeneous only at the macroscopic level. Below the macroscopic scale, heterogeneity exists as nanoscale clusters or bubbles form especially near critical conditions, depending on the regimes as defined by the Widom line. The coupling of van der Waals interactions with molecular motions, along with the possible compositional variations around such heterogeneity, can cause multicomponent supercritical fluids to have transport and reaction processes that can differ from subcritical fluids, including local fluid instability. For multicomponent mixtures, these instabilities are poorly understood. Microgravity experiments are expected to alter the physical cause for the instability, thus potentially revealing fluid dynamics unseen previously. During trans-critical phase change processes, surface instabilities (hydrodynamic instabilities) will affect burning rates and limit combustion conditions. Gravity has a significant effect on instabilities, and hence, microgravity will enable conditions for study not previously available.

A component of this proposed research that should be pursued is comparison of (trans) critical properties of petroleum fuels vs. sustainable alternate fuels (SAF). This may or may not need a microgravity environment for determination but could well be very important given that, in the near future, advanced systems may be optimized based on performance of petroleum fuels under near critical conditions, but such thresholds may differ substantially for SAF risking the optimized performance of the engines.

**Need for and Opportunities in Microgravity**

Thermodynamic and transport properties of multicomponent trans-critical mixtures rely on empirical mixing rules for making predictions. While molecular dynamics (MD) simulations of the thermodynamic and transport properties of supercritical hydrocarbon mixtures are becoming available, no reliable experimental data exist to test the empirical mixing rules or the MD simulations for such multi-component mixtures. Reliable measurement of these properties must eliminate complicating effects associated with a buoyant environment.

As indicated above, buoyancy due to gravity complicates terrestrial studies. Since buoyancy forces are linearly dependent on mass (or ambient pressure), and critical pressures of liquid hydrocarbons are typically 25-30 atm, studies in one g are aggravated by buoyancy. Small temperature variations in the apparatus can lead to large changes in the behavior of the fluid as it approaches its critical state. Trajectories of droplets entering into a trans-critical fluid will likely be altered due to the property changes of the fluid and a resultant impact on drag on the particle [25]. To this end, microgravity studies are beneficial to trans-critical examinations in at least two configurations: (i) a suspended droplet, and (ii) a liquid jet. In the first configuration, trans-critical conditions occur if the droplet is suspended in a high-pressure, high-temperature, environment. In the second configuration trans-criticality develops when the jet is injected into a quiescent or coflowing gaseous environment at suitably high pressure and high temperature. Both non-reacting and reacting conditions can be considered. With regards to a suspended droplet, NASA researchers under the microgravity program have already provided subcritical experimental and computational results on the droplet ignition and burning behavior in microgravity [21, 26, 27]. However, studies on trans-critical combustion have been limited [28, 29]. Microgravity studies of liquid jet combustion have been carried out almost exclusively at low pressures (e.g., [30, 31]), while reacting and nonreacting trans-critical experiments were typically performed at one g [32] with significant complications due to buoyancy.

By far the greatest need for the microgravity experiments is to minimize/eliminate buoyancy that is competitive with other transport processes of importance to combustion, e.g., molecular diffusion and radiation. By eliminating free convection as driven by buoyancy forces, symmetry can often be obtained in combustion problems making analysis and experimentation simpler and more useful. Furthermore, high-pressure conditions will emphasize molecular transport and modify the phase change process. Combined microgravity and high-pressure conditions will allow isolation of molecular transport processes, particularly for multicomponent hydrocarbon mixtures that have limited critically reviewed data of poorly characterized uncertainty, permitting studies to improve their fundamental understanding.

Long duration (microgravity) flight experiments are critical to establishing equilibrium conditions under trans-critical conditions. Comparing the timescales for fluid state changes with those of mixing, diffusion, and reaction is necessary in order to establish the validity of current theories and modeling approaches [2, 33]. Critical slowing [17], which can extend thermodynamic relaxation times to minutes or hours at near-critical conditions, makes the equilibrium assumption of further concern. Regarding local clustering, the agglomeration and integration of molecular clusters and nano-bubbles, and spatially sparsely separated clusters, can take time to evolve. This phenomenon of course is strongly dependent on the components in the mixture and the variation in their respective critical temperatures and pressures, as well as their relative mixture fraction and solubility, etc. Such experiments simply cannot be performed on earth since small temperature differences induce buoyant flows that fundamentally perturb critical conditions and processes.

A possibility exists that long relaxation timescales of thermodynamic properties compared to mixing timescales could lead to molecular structure persisting into the high temperature region. Pyrolysis, soot, or cool flame reactions are more likely to be directly impacted since they occur at temperatures closer to the likely critical temperatures. Continued research into cool flames shows promise for providing insight into the impacts of near-critical molecular structure on reactions. Further, whether and how trans-criticality impacts the transition to and from hot flames may provide additional understanding of chemical kinetic-controlled processes.

**Key Recommendations**

* Coordinate with other agencies to measure fundamental properties and develop models for key multi-component mixtures, as well as to maximize the impact on terrestrial technologies. This effort has already been initiated with AFOSR (Dr. Chiping Li) and NASA (Dr. Jeff Moder), who have expressed interest in coordinated efforts in development of tools useful for development of rocket engines and advanced aeroengines. In addition, DoE and other DoD agencies are other likely partners due to their interests in advanced high-pressure diesel and gas turbine engines. Applications to endothermic fuels applicable for hypersonic flight will involve experiments solely on hydrocarbon mixtures.
* Develop hardware and research capabilities for investigation of trans-critical properties and combustion phenomena for longer duration experiments (greater than 10s of seconds) under microgravity conditions needed to study transition from non-equilibrium to equilibrium conditions, facilitated in long-duration space flight. The main high pressure/temperature (combustion) chamber can be modeled after an existing facility developed at NASA GRC and is presently used for one g and drop tower experiments.
* Design and implement multiple configuration inserts (single, multiple droplets, and jets for example) for the combustion chamber with appropriate diagnostics to enable testing at varying conditions and measurement of properties of mixtures with multiple components.
* Carry out model development, property measurements and combustion studies focusing on multi-component mixtures/blends selected to facilitate interpretations and extrapolate results to other mixtures including SAFs. Consider blends, for example, of compounds below that have similar *Tc* but different *pc* values, while *n*-propylbenzene and *iso*-propyl-benzene have similar *Tc* and *pc*, but different Negative Temperature Coefficient behaviors.

|  |  |  |
| --- | --- | --- |
|  | | |
| Substance | *Tc* (K) | *pc* (bar) |
| Undecane | 639 | 19.8 |
| *n*-Propylbenzene | 638 | 32.0 |
| *iso*-Propylbenzene | 631 | 32.1 |
| Nitrogen | 127 | 33.9 |

* Examine and determine relaxation times to attain thermodynamic equilibrium in near critical regimes and compare to those of other rate-controlled processes. Establish state properties under equilibrated conditions.
* Open and continue communications with key international organizations such as JAXA, ELGRA, and ZARM.

Additional details on a plan, diagnostic tools, and needs, etc., for zero gravity research for trans-critical phenomena and combustion can be obtained from [34].

**References**

[1] M. Oschwald, J.J. Smith, R. Branam, J. Hussong, A. Schik, B. Chehroudi, and D. Talley, *Injection of fluids into supercritical environments*, Combustion Science and Technology, 178(1-3) (2006) 49-100. <https://doi.org/10.1080/00102200500292464>

[2] R.N. Dahms, *Understanding the breakdown of classic two-phase theory and spray atomization at engine-relevant conditions*, Physics of Fluids **28**, 042108 (2016), https://doi.org/10.1063/1.4946000

[3] P.H. van Konynenburg, R.L. Scott, *Critical lines and phase equilibria in binary van der Waals mixtures*, Philosophical Transactions of the Royal Society A, 298 (1980) 495-540. https://doi.org/10.1098/rsta.1980.0266

[4] H.E. Stanley, Introduction to Phase Transitions and Critical Phenomena, Oxford University Press: London, 1971. ISBN: 0195053168, 9780195053166

[5] J.V. Sengers, *Transport properties of fluids near critical points*, International Journal of Thermophysics, 6 (3) (1985) 203-232. <https://doi.org/10.1007/BF00522145>

[6] M. Raju, D.T. Banuti, P.C. Ma, M. Ihme, *Widom lines in binary mixtures of supercritical fluids*, Scientific Reports 7 (1), (2013) 1-10. https://doi.org/10.1038/s41598-017-03334-3

[7] W.A. Sirignano, Fluid Dynamics and Transport of Droplets and Sprays, Cambridge University Press, 1999. <https://doi.org/10.1017/CBO9780511529566>

[8] S.K. Aggarwal, C. Yan and G. Zhu, *Transcritical vaporization of a liquid fuel droplet in a supercritical ambient*, Combustion Science and Technology, 174(9) (2002) 103-130. https://doi.org/10.1080/00102200290021399

[9] T. Toki and J. Bellan, *Direct numerical simulation of single-species and binary-species boundary layers at high pressure,* AIAA Scitech 2021 Forum. AIAA 2021-0682. January 2021.

[10] L. Jofre and J. Urzay, *Transcritical diffuse-interface hydrodynamics of propellants in high-pressure combustors of chemical propulsion systems,* Progress in Energy and Combustion Science, 82 (2021) 100877. https://doi.org/10.1016/j.pecs.2020.100877

[11] G. Zhu and S. K. Aggarwal, *Transient supercritical droplet evaporation with emphasis on the effects of equation of state*, International Journal of Heat and Mass Transfer, 43(7), (2000) 1157-1171. https://doi.org/10.1016/S0017-9310(99)00197-0

[12] J.M.H. Levelt Sengers, *Mean-field theories, their weaknesses and strengths*, Fluid Phase Equilibria, 159 (1999) 3-17. <https://doi.org/10.1016/S0378-3812(99)00096-5>

[13] R.N. Dahms and J.C. Oefelein, *On the transition between two-phase and single-phase interface dynamics in multicomponent fluids at supercritical pressures,* Physics of Fluids 25 (092103) (2013) 1–24. https://doi.org/10.1016/S0378-3812(99)00096-5

[14] R.C. Reid, J.M. Prausnitz, B.E. Polling, The Properties of Liquids and Gases, 4th Ed., McGraw-Hill, New York, 1987. OSTI Identifier: 6504847

[15] J.F. Ely, H.J.M. Hanley, *Prediction of transport properties. 1. Viscosity of fluids and mixtures,* Industrial & Engineering Chemistry Fundamentals 20(4) (1981) 323–332. https://doi.org/10.1021/i100004a004

[16] R.B. Bird, W.E. Stewart, E.N. Lightfoot, Transport Phenomena, John Wiley and Sons, Incorporated, New York, 1960.

[17] J.O. Hirschfelder, C.F. Curtiss, R.B. Bird, Molecular Theory of Gases and Liquids, 2nd Edition., John Wiley and Sons, Incorporated, New York, 1964.

[18] S. Takahashi, *Preparation of a generalized chart for the diffusion coefficients of gases at high pressures*, Journal of Chemical Engineering of Japan, 7(6) (1974) 417–420. https://doi.org/10.1252/jcej.7.417

[19] S.B. Kiselev and D.G. Friend, *Cubic crossover equation of state for mixtures*, Fluid Phase Equilibria, 162(1) (1999) 51-82. https://doi.org/10.1016/S0378-3812(99)00182-X

[20] A. Movaghar, R. Lawson, F.N. Egolfopoulos, *Confined spherically expanding flame method for measuring laminar flame speeds: Revisiting the assumptions and application to C1C4 hydrocarbon flames*, Combustion and Flame, 212 (2020) 79–92. https://doi.org/10.1016/j.combustflame.2019.10.023

[21] T.I. Farouk, D. Dietrich, D. and F.L. Dryer, *Three stage cool flame droplet burning behavior of n-alkane droplets at elevated pressure conditions: Hot, warm and cool flame,* Proceedings of the Combustion Institute, 37(3) (2019) 3353-3361. https://doi.org/10.1016/j.proci.2018.09.015

[22] P.G. Debenedetti, I.B. Petsche, R.S. Mohamed, *Clustering in supercritical mixtures: Theory, applications and simulations*, Fluid Phase Equilibria 52 (1989) 347-356. https://doi.org/10.1016/0378-3812(89)80340-1

[23] S.C. Tucker, *Solvent density inhomogeneities in supercritical fluids*, Chemical Reviews, 99 (2) (1999) 391-418. <https://doi.org/10.1021/cr9700437>

[24] [P.E. Savage](https://aiche.onlinelibrary.wiley.com/action/doSearch?ContribAuthorRaw=Savage%2C+Phillip+E), [S. Gopalan](https://aiche.onlinelibrary.wiley.com/action/doSearch?ContribAuthorRaw=Gopalan%2C+Sudhama), [T.I. Mizan](https://aiche.onlinelibrary.wiley.com/action/doSearch?ContribAuthorRaw=Mizan%2C+Thamid+I), [C.J. Martino](https://aiche.onlinelibrary.wiley.com/action/doSearch?ContribAuthorRaw=Martino%2C+Christopher+J), [E.E. Brock](https://aiche.onlinelibrary.wiley.com/action/doSearch?ContribAuthorRaw=Brock%2C+Eric+E), *Reactions at supercritical conditions: Applications and fundamentals,* AIChE Journal, 41(7) (1995), pp. 1723-1778, https://doi.org/10.1002/aic.690410712

[25] Y. Fujitani, *Drag Coefficient of a Spherical Droplet Immersed in a Near-Critical Binary Fluid Mixture*, Journal of the Physics Society of Japan, 83 (2014) 024401. https://doi.org/10.7566/JPSJ.83.024401

[26] V. Nayagam, D.L. Dietrich, P.V. Ferkul, M.C. Hicks, and F.A. Williams, *Can cool flames support quasi-steady alkane droplet burning?* Combustion and Flame, 159(12) (2012) 3583-3588. https://doi.org/10.1016/j.combustflame.2012.07.012

[27] V. Nayagam, D.L. Dietrich, M.C. Hicks, and F.A. Williams, *Cool-flame extinction during n-alkane droplet combustion in microgravity,* Combustion and Flame, 162(5) (2015) 2140-2147. https://doi.org/10.1016/j.combustflame.2015.01.012

[28] G.M. Faeth, D.P. Dominicis, J.F. Tulpinsky, and D.R. Olson, *Supercritical Bipropellant Droplet Combustion,* Proceedings of the Combustion Institute, 12 (1969) 9-18. https://doi.org/10.1016/S0082-0784(69)80387-5

[29] H. Nomura, S. Nakaya and M. Tsue, *Microgravity research on quasi-steady and unsteady combustion of fuel droplet at high pressures,* Edited by: J. Bellan, High-Pressure Flows for Propulsion Applications, 260 (2020) 1-47. https://doi.org/10.2514/5.9781624105814.0001.0048

[30] Q. Wang, L. Hu, S. Wang, S. Wang, S.H. Chung, O. Fujita, *Blowout of non-premixed turbulent jet flames with coflow under microgravity condition*, Combustion and Flame, 210 (2019) 315-323. https://doi.org/10.1016/j.combustflame.2019.08.041

[31] A. Markan, H. R. Baum, P. B. Sunderland, J. G. Quintiere, J. L. de Ris, *Transient ellipsoidal combustion model for a porous burner in microgravity*, Combustion and Flame, 212 (2020) 93-106. <https://doi.org/10.1016/j.combustflame.2019.09.030>

[32] G. Singla, P. Scouflaire, C. Rolon, S. Candel, *Transcritical oxygen/transcritical or supercritical methane combustion*, Proceedings of the Combustion Institute, 30(2) (2005) 2921-2928. <https://doi.org/10.1016/j.proci.2004.08.063>

[33] C. Crua, J. Manin, L.M. Pickett, On the transcritical mixing of fuels at diesel engine conditions, Fuel  [208](https://www.sciencedirect.com/science/journal/00162361/208/supp/C), (2017), pp. 535-548. <https://doi.org/10.1016/j.fuel.2017.06.091>.

[34] H. Curran, S. Goldsborough, M. Lightfoot, H. Wang, R. Yetter, S. Aggarwal, M. Colket, “Summary Report and Recommendations to NASA from the Science Definition Team for High-Pressure, Trans-Critical Research,” February 2021. Available from Dr. Dan Dietrich, or [med@colket.org](mailto:med@colket.org).