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Project Title: Residence Time Driven Flame Spread Over Solid Fuels  Program/Discipline:  Program/Discipline-  Element Subdiscipline:  COMBUSTION SCIENCE—Combustion science  Element Subdiscipline:  Literate Agency Name:  TechPort: No  No  Liteman Research Program Elements: None  Space Biology Cross-Element: None  Space Biology Special Category: None  PL Emul: noof-Subatacharice/genal.com  PC Organization Type: UNIVERSITY PL Organization Type: UNIVERSITY PL Organization Name: Son Diego State University  PL Address 1: Solid Campanile Drive, Mechanical Engineering Department  PL Address 2:  PL Web Page:  City: San Diego Sate CA  Comments:  Project Type: Flight Solidation / Funding 2009 Combustion Science Scart Date: No. of Post Decre: No. of Post Decre: No. of Post Decre: No. of Post Decre: No. of Bachelor's Candidates: 4 No. of Bachelor's Candidates: 4 No. of Bachelor's Candidates: 6 No. of Bachelor's Candidates: No. of Bachelor's Candidates: 1 No. of Bachelor's Candidates: 3 No. of Bachelor's Candidates: 3 No. of Bachelor's Candidates: 3 No. of Bachelor's Candidates: 4 No. of Bachelor's Candidates: 5 No. of Bachelor's Candidates: 5 No. of Bachelor's Candidates: 6 No. of Bachelor's Candidates: 7 No. of Bachelor's Candidates: 8 No. of Bachelor's Candidates: 8 No. of Bachelor's Candidates: 8 No. of Bachelor's Candidates: 9 No. of Bachelor's Candidates: 1 No	Fiscal Year:	FY 2017	Task Last Updated:	FY 01/31/2017
Physical Sciences   Physical Sciences   Physical Sciences   Program/Discipline:   Prog	PI Name:	Bhattacharjee, Subrata Ph.D.		
Program/Discipline:	Project Title:	Residence Time Driven Flame Spread Over Solid Fuels		
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Human Research Program Elements: None  Human Research Program Risks: None  Space Biology Element: None  None  Space Biology Cross-Element None  Plorganization Type: None  Pl Granization Type: UNIVERSITY Phone: 619-594-6080  Organization Type: San Diego State University  Pl Address 1: 5500 Campanile Drive, Mechanical Engineering Department  Pl Address 2: Pl Web Page:  City: San Diego State University  Pl Web Page:  City: San Diego State University  Project Type: Flight Solicitation / Funding Source: NNII09ZTT001N  Start Date: 0406/2015 End Date: 0405/2020  No. of PhD Candidates: 1 No. of PhD Candidates: 1 No. of Master' Degrees: 2  No. of PhD Candidates: 4 No. of Master' Degrees: 2  No. of Master's Candidates: 6 Monitoring Center: NASA GRC  Contact Monitor: Olson, Sandra Contact Phone: 216-433-2859  Contact Monitor: Sandra Contact Phone: 216-433-2859  Elight Program: ISS  Flight Assignment: ISS  Flight Assignment: NNIXISAGIIG  Wakai, Kayanoi Ph.D. (Gifu University)  Takahashi, Shaber Ph.D. (Gain Diego State University)  Takahashi, Shaber Ph.D. (Gifu University)  Wakai, Kayanoi Ph.D. (Gifu University)  Wakai Kayanoi Ph.D. (Gifu University)	Program/Discipline Element/Subdiscipline:	COMBUSTION SCIENCECombustion science		
Human Research Program Risks: None Space Biology Element: None Space Biology Cross-Element Discipline: None Space Biology Cross-Element Discipline: Prof I battacharjee@email.com Fax: FY PI Cranil: Prof I battacharjee@email.com Fax: FY PI Organization Type: UNIVERSITY Phone: 619-594-6080 Organization Name: San Diego State University PI Address 1: 5500 Campanile Drive, Mechanical Engineering Department FPI Address 2: FI Web Prage: City: San Diego State University FI Web Prage: City: San Diego State: CA Comments: Project Type: Flight Solicitation / Funding 2009 Combustion Science National Professional District: 53 Comments: Project Type: Flight Solicitation / Funding 2009 Combustion Science National Professional District: National Professional District: Saure: National Professional District	Joint Agency Name:		TechPort:	No
Space Biology Cross-Element Space Biology Cross-Element Space Biology Cross-Element Space Biology Special Category: None PI Email: prof_Bhattacharjee@gmail.com Fax: FY Pl Organization Type: UNIVERSITY Pl Organization Type: UNIVERSITY Pl Address 1: S500 Campanile Drive, Mechanical Engineering Department PI Address 2: PI Web Page: City: San Diego Sate University PI Address 2: PI Web Page: City: San Diego Sate Organization Name: Project Type: Flight Solicitation / Funding Source: NNH09ZITTO01N Start Date: O406/2015 Fight Solicitation / Funding Source: NNH09ZITTO01N Start Date: O406/2015 Fand Date: O406/2015 Fand Date: O406/2015 For Does: No. of PhD Degrees: No. of PhD Degrees: No. of Master' Degrees: Source: No. of Master' Scandidates: 1 No. of Master' Scandidates: 1 No. of Master' Scandidates: Source: No. of Bachelor's Source: No. of Bachelor's Candidates: Source: Source: Source: No. of Bachelor's Candidates: Source: Source: Source: No. of Master' Degrees: Source: Source: No. of Master' Degrees: Source: No. o	<b>Human Research Program Elements:</b>	None		
Space Biology Cross-Element Discipline: Discipline: Discipline: Discipline: PE Email: pmof.bhattacharjee@cmail.com prof.bhattacharjee@cmail.com prof.bhattacharje	Human Research Program Risks:	None		
Discipline: "None Space Biology Special Category: None PH Organization Type: UNIVERSITY Phone: 619-594-6080 Organization Name: San Diego State University PH Address 1: 5500 Campanile Drive, Mechanical Engineering Department PH Address 2: PH Web Page: City: San Diego State University PH Address 2: PH Web Page: City: San Diego State: CA Zip Code: 92182-0001 Congressional District: 53 Comments: Project Type: Flight Solicitation / Funding 2009 Combustion Science NN1109ZTT001N Start Date: 04-06/2015 End Date: 04-08/2020 No. of Post Does: 0 No. of PhD Degrees: No. of PhD Candidates: 1 No. of Master' Degrees: 2 No. of Bachelor's Candidates: 4 No. of Bachelor's 8 Degrees: 8 No. of Bachelor's Candidates: 6 Monitoring Center: NASA GRC Contact Email: Sandra Obsonitionusa gov Flight Program: ISS Flight Assignment: ISS Key Personnel Changes/Previous PI: COI Name (Institution): Miller, Fletcher Ph.D. (San Diego State University) Takahashi, Shuheir Ph.D. (Grift University) Wakai, Kazunori Ph.D. (Grift University) Wakai, Kazunori Ph.D. (Grift University) Wakai, Kazunori Ph.D. (Grift University) Performance Goal No.:	Space Biology Element:	None		
PI Email: prof bhattacharies@mail.com Fax: FY PI Organization Type: UNIVERSITY Phone: 619-594-6080 Organization Name: San Diego State University PI Address 1: 5500 Campanile Drive, Mechanical Engineering Department  PI Address 2: PI Web Page: City: San Diego State University PI Web Page: City: San Diego State University Comments:  Project Type: Flight Solicitation / Funding 2009 Combustion Science NNH09ZTT001N Start Date: 04/06/2015 End Date: 04/05/2020 No. of Pbat Does: 0 No. of PhD Degrees: No. of Pbat Does: 0 No. of Master' Degrees: 2 No. of Pbat Candidates: 1 No. of Master' Degrees: 2 No. of Master's Candidates: 4 No. of Bachelor's Degrees: 8 No. of Bachelor's Candidates: 6 Monitoring Center: NASA GRC Contact Monitor: Olson, Sandra Contact Honitor: Sandra Olson@mass.gov Flight Program: ISS Flight Assignment: ISS Flight Assignment: ISS COI Name (Institution): Willer, Fletcher Ph.D. (San Diego State University) Takahashi, Shahel Ph.D. (Gifu University) Paolini, Christopher Ph.D. (Gifu University) Wakai, Kazunori Ph.D. (Gifu University) Wakai, Kazunori Ph.D. (Gifu University) Grant/Contract No.: NNXI5AG11G	Space Biology Cross-Element Discipline:	None		
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Zip Code: 92182-0001 Congressional District: 53  Comments:  Project Type: Flight Solicitation / Funding Source: NNH09ZTT001N  Start Date: 04/06/2015 End Date: 04/05/2020  No. of Post Does: 0 No. of PhD Degrees:  No. of PhD Candidates: 1 No. of Master' Degrees: 2  No. of Master's Candidates: 4 No. of Bachelor's Degrees: 8  No. of Bachelor's Candidates: 6 Monitoring Center: NASA GRC  Contact Monitor: Olson, Sandra Contact Phone: 216-433-2859  Contact Email: Sandra Olson@nasa.gov  Flight Program: ISS  Key Personnel Changes/Previous PI:  COI Name (Institution): Miller, Fletcher Ph.D. (San Diego State University) Paolini, Christopher Ph.D. (Gifu University) Wakai, Kazunori Ph.D. (Gifu University)  Wakai, Kazunori Ph.D. (Gifu University)  Wakai, Kazunori Ph.D. (Gifu University)  Reperformance Goal No.:	PI Web Page:			
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No. of Post Docs:  No. of PhD Candidates:  1	Project Type:	Flight		
No. of PhD Candidates:  1	Start Date:	04/06/2015	End Date:	04/05/2020
No. of Master's Candidates:  4	No. of Post Docs:	0	No. of PhD Degrees:	
No. of Bachelor's Candidates:  Olson, Sandra  Contact Monitor:  Olson, Sandra  Contact Phone:  216-433-2859  Contact Email:  Sandra.Olson@nasa.gov  Flight Program:  ISS  ISS  Flight Assignment:  Key Personnel Changes/Previous PI:  COI Name (Institution):  Miller, Fletcher Ph.D. (San Diego State University) Paolini, Christopher Ph.D. (Gifu University) Wakai, Kazunori Ph.D. (Gifu University) Wakai, Kazunori Ph.D. (Gifu University)  Performance Goal No.:	No. of PhD Candidates:	1		
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Flight Assignment:  Key Personnel Changes/Previous PI:  COI Name (Institution):  Miller, Fletcher Ph.D. (San Diego State University) Paolini, Christopher Ph.D. (San Diego State University) Takahashi, Shuhei Ph.D. (Gifu University) Wakai, Kazunori Ph.D. (Gifu University)  MNX15AG11G  Performance Goal No.:	Contact Email:	Sandra.Olson@nasa.gov		
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NOTE: Continuation of "Residence Time Driven Flame Spread Over Solid Fuels," grant # NNX10AE03G. Flame spread over solid fuels in an opposed-flow environment has been investigated for over four decades for understanding the fundamental nature of hazardous fire spread. The appeal for this configuration stems from the fact that flame spread rate remains steady, even if the flame itself may grow in size. For practical fire safety issues, however, wind-assisted flame spread is more relevant.

However, these two regimes have always been studied in isolation without much effort to establish a connection, even though the underlying mechanism of flame spread is the same in all regimes. Sitting between the two regimes are high-residence time flames, as found in a low-velocity or quiescent microgravity environment. Residence time is the time spent by an oxidizer in the combustion zone. Such flames, which are of interest on their own merit due to fire safety issues in spacecraft, offer some unique characteristics because of the high residence time. Radiation becomes dominant and, based on previous space experiments and analysis, we contend that a vigorously spreading flame on Earth becomes self-extinguishing in a microgravity environment under certain conditions such as the fuel thickness being greater than a critical value.

The proposed research uses a comprehensive approach-- a novel experimental set up and a theoretical framework based on scaling and numerical modeling-- to investigate flame spread driven by varying residence time, from blow-off extinction in an opposed-flow configuration through high residence time flame to blow-off extinction in a concurrent-flow configuration. At the heart of this proposal is a novel but simple experiment where the residence time of the oxidizer can be controlled and high residence time flames can be established for a long duration (compared to drop towers). As a proof of concept, we have constructed a flame tower at San Diego State University (SDSU) in which, after a sample is ignited, the sample holder, placed in an open moveable cart, can be traversed at any desired speed upward or downward, creating an external flow that can augment or mitigate the buoyancy-induced flow. Preliminary results show that we can control the residence time and create flames in different regimes, including a transition between a wind-aided and wind-opposed configuration. At Gifu University in Japan, we have been developing an interferometry based imaging system which we intend to enhance to capture the thermal footprint of a flame's leading edge. The leading edge is central to our understanding of mechanism of flame extinction. Further development of this technology will enable us to integrate diagnostics in future space based experiments and provide validation data to a comprehensive numerical model. The comprehensive model, to be built upon our existing two-dimensional model, will solve an unsteady, three-dimensional, Navier stokes equation with finite rate kinetics in the gas and solid phases and radiation in the gas phase. The software implementation will be object-oriented and utilize a new technology called Web Services that will decouple various sub-models and enhance parallel execution.

The radiation model will also be refined by including the equilibrium composition of species for finding radiative properties in high residence-time flames. The comprehensive model, tested against available theory, data in literature, and data generated at SDSU and Gifu, was applied to test the three hypotheses presented in the preceding grant regarding flame extinguishment in a microgravity environment. A successful outcome of that project is leading to a well thought out space-based experiment on the mechanism of flame extinction in a gravity free environment. We have received authority to proceed to Preliminary Design Review.

## Rationale for HRP Directed Research:

**Task Description:** 

Our research has four components. (a) We have built three experimental setups at SDSU: Flame Tower where a test sample can be traversed up or down at any desired velocity; Flame Stabilizer where the motion of the flame can be arrested by moving the sample exactly at the speed of the flame spread in the opposite direction; and a rotating Flame Tunnel where a combustion tunnel can be oriented at any desired angle to study the interaction of buoyancy and forced flow; (b) Theoretical and computational work that explores the similarity and differences between the mechanisms flame spread in a zero gravity space environment and on Earth; (c) Support the space based experiment (in the SoFIE project) to establish extinction mechanism of flames.; (d) Develop software tools for data analysis and share those with the research community.

## Research Impact/Earth Benefits:

The data that we are acquiring in the experiments provide the research community with a comprehensive set of results for testing different theories of flame spread in a normal gravity environment. Moreover, by controlling the residence time, various regimes of flame spread, including the microgravity regime, can be explored in the Flame Tower. Our theoretical work predicts a fuel thickness beyond which steady flame spread is unsustainable in a gravity free environment. If we are successful in establishing a critical thickness, this will have a powerful impact on making fire resistant environment for humans in space.

Significant progress has been made during this period of the project. The major highlight of this period is further analysis of BASS-II experimental results (obtained from experiments aboard International Space Station-ISS) and publication of two archival journal articles based on these results. We also presented several conference papers. In this period we have significantly expanded the capabilities of our Flame Stabilizer apparatus for automated data acquisition. One of our major accomplishment is the publication in the 36th International Symposium on Combustion, the abstract of which is highlighted below (see also Bibliography section):

Task Progress:

The three regimes of opposed-flow flame spread – radiative, thermal, and kinetic regimes – are well known. For thermally thin fuels, the spread rate is independent of opposing flow velocity in the thermal regime. It decreases with an increase in the flow velocity in the kinetic regime, leading to blow off extinction. In the radiative regime which occurs mostly in a buoyancy-free environment of microgravity, the spread rate decreases with a decrease in flow velocity leading to radiative extinction unless the oxygen level is very high. In a recent experiment aboard the International Space Station, thin sheets of (Poly(methyl methacrylate) (PMMA) were ignited in a flow tunnel with the opposing flow varying over a wide range. All three regimes of flame spread were captured in a single set of experiments for the first time. Instantaneous spread rates were obtained from digital video processing and compared with a computational model in all three regimes along with the evolution of flame shapes. Spread rates in the radiative and thermal regimes are also compared with existing theories of flame spread in the thermal and the radiative regime producing remarkable qualitative agreement.

**Bibliography Type:** 

Description: (Last Updated: 06/13/2025)

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Abstracts for Journals and Proceedings	Carmignani L, Bhattacharjee S. "Flame Spread over PMMA Samples and Blow-Off Extinction for Different Angles." 32nd Annual Meeting of the American Society for Gravitational and Space Research, Cleveland, OH, October 26-29, 2016. 32nd Annual Meeting of the American Society for Gravitational and Space Research, Cleveland, OH, October 26-29, 2016., Oct-2016
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Abstracts for Journals and Proceedings	Lange G, Kievens K, Bhattacharjee S. "Measurement and Computations of Thermal Radiation in Downward Spreading Flame." Western States Section Technical Meeting of the Combustion Institute, Spring Technical Meeting, University of Washington, Seattle, WA, March 21-22, 2016. WSS Technical Meeting of the Combustion Institute, Spring Technical Meeting, University of Washington, Seattle, WA, March 21-22, 2016., Mar-2016
Articles in Peer-reviewed Journals	Bhattacharjee S, Simsek A, Miller F, Olson S, Ferkul P. "Radiative, thermal, and kinetic regimes of opposed-flow flame spread: A comparison between experiment and theory." Proceedings of the Combustion Institute. In press, corrected proof. Available online 17 August 2016. <a href="http://dx.doi.org/10.1016/j.proci.2016.06.025">http://dx.doi.org/10.1016/j.proci.2016.06.025</a> , Aug-2016
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Papers from Meeting Proceedings	Bhattacharjee S, Carmignani L, Simsek A. "Boundary Layer Effect on Opposed-Flow Flame Spread in the Microgravity Regime." 46th International Conference on Environmental Systems, Vienna, Austria, July 10-14 2016. ICES paper 2016-387. <a href="http://hdl.handle.net/2346/67700">http://hdl.handle.net/2346/67700</a> ; accessed 2/1/17. , Jul-2016