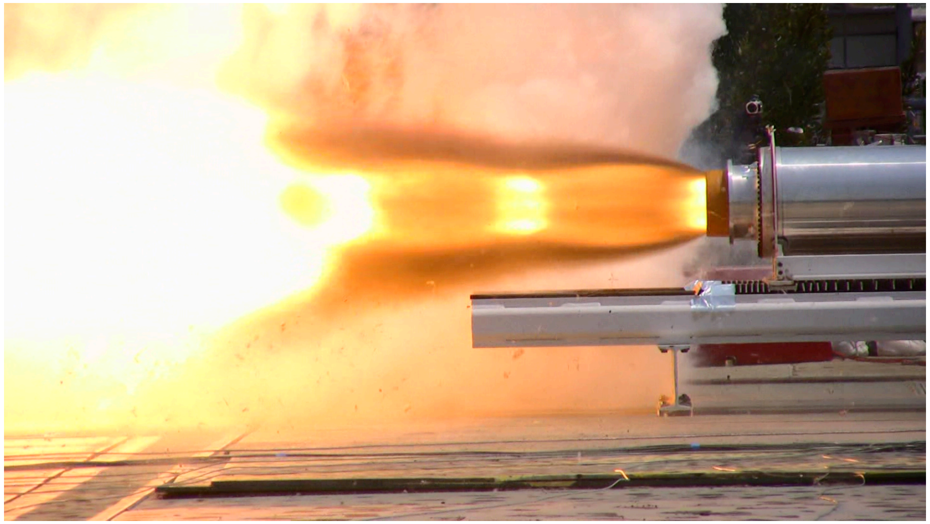
AA284A
Advanced Rocket Propulsion

Session 1a. 1/7/20 - Course Organization



Brian Cantwell - Department of Aeronautics and Astronautics Stanford University
Greg Zilliac – NASA Ames Research Center
Arif Karabeyoglu – Koc University Istanbul

Course approach – The course will comprise 20 topic area sessions. Topics 1 to 5, 9 and 17 will be in the form of lectures presented by the instructors. The remaining 13 topics will be the subject of student led presentations and discussions. Several students will prepare presentation materials and lead each topic discussion. A typical class session would comprise two or three student presentations describing the results of their research on particular themes related to the topic area of that session.

All students need to submit their preferences in the form of a rank ordering of all 13 topic areas to Prof. Cantwell by 3:00 Wednesday Jan 8. Final topic area assignments will be provided in class on Jan 9.

Prior to the Jan 14 lecture, students must submit a one paragraph proposal identifying the theme that they plan to research and present in their assigned topic area. The theme can be from a list of suggested themes prepared by the instructors or the student can propose their own theme. Note that the first student led presentation is on Jan 23.

Within a week following their presentation each student will submit an individual written report approximately 10 pages long on their topic area/theme. The report should be in the format used for papers submitted to the AIAA Propulsion and Energy Forum (used to be the Joint Propulsion Conference). See https://www.aiaa.org/events-learning/events/Technical-Presenter-Resources

Students who are signed up for three units of credit will be assigned four topics (four written reports). Students signed up for one unit will be assigned two topics (two written reports). A list of resource materials for each session will be provided by the instructors at the beginning of the course although students are free to include additional resources in their presentation if they wish. All students are expected to become familiar with the topic of each session and to provide input to the class discussion during the session.

Grading – The final course grade will be determined by three, approximately equally weighted, elements: 1) the quality of materials prepared for each topic area/theme led by the student, 2) the quality and completeness of the student's report(s) and 3) the quality of the student's in-class participation in the discussion of all the various topic areas covered in the course.

Resources –Resources for this class can be found on my website https://web.stanford.edu/~cantwell/ which includes Course Materials for AA283 and AA103. Within the AA284 Course Materials folder is a folder containing Prof Karabeyoglu's AA 284 Lectures. Also provided in the AA284A Course Materials folder are the lectures and many of the references identified with the AA284A specific topic areas.

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AA284A Resources Folder Jan 7, 2020

AA284A_Resources

Favorites: user, AirDrop, All My Files, iCloud Drive, Applications, Pictures, Desktop, Documents, Downloads

Devices

Tags: Red, Orange, Yellow, Green, Blue, Purple, Gray, All Tags...

Name

- Bilstein, Roger E. Stages to Saturn A Technological History of the ApolloSaturn Launch VehiclesNASA SP-4206 1980.pdf
- Blount et al CDC Urinary Perchlorate and Thyroid Hormone Levels in Adolescent and Adult Men and Women Living in the United States.pdf
- Borowski et al, Nuclear Thermal Rocket Vehicle Design Options NASA TM 107071 AIAA-93-4170.pdf
- Camberos and Moubry, Chemical Equilibrium Analysis with the Method of Element Potentials 2001-0873.pdf
- Cantwell, Karabeyoglu and Altman, Recent Advances in Hybrid Propulsion IJEMCP_9_(4)_305-326_2010.pdf
- Carter et al, Design Trade Space for a Mars Ascent Vehicle Acta Astronautica Vol 45 1999.pdf
- Chandler et al, Feasibility of a single port Hybrid Propulsion system for a Mars Ascent Vehicle ActaAstronautica (69) 2011.pdf
- Chiavarini and Kuo, Fundamentals of Hybrid Rocket Combustion and Propulsion AIAA.pdf
- Clasen, The Numerical Solution of the Chemical Equilibrium Problem RAND 1965.pdf
- Culick and Yang, Prediction of the Stability of Unsteady Motions in Solid-Propellant Rocket Motors AIAA 1990.pdf
- Culick, Combustion Instabilities in Liquid-Fueled Propulsion Systems AGARD 1988.pdf
- Glushko, Development of Rocketry and Space Technology in the USSR.pdf
- Goebel and Katz, Fundamentals of Electric Propulsion Ion and Hall Thrusters JPL 2008.pdf
- Greason and Bennett The economics of space an industry ready to launch.pdf
- Henry, Humble and Larson, Hybrid Rocket_Design Example AIAA 1993-2048.pdf
- Hodapp, Germanys Rocket Development in World War II Univ Hawaii 2013 .pdf
- Huzel and Huang, Design_Of_Liquid_Propellant_Rocket_Engines NASA 1967.pdf
- Jahn and Choueiri, Electric Propulsion Encyclopedia of Physical Science and Technology 2002.pdf
- Jens et al, Hybrid Combustion at Elevated Pressure JPP Oct 22 2019.pdf
- Johnson, W, Contents and Commentary on William Moore's A Treatise on the Motion of Rockets and an Essay on Naval Gunnery.pdf
- Karabeyoglu and Cantwell, Combustion of Liquefying Hybrid Propellants Part 2 Stability of Liquid Films part 2 JPP Vol 18 2002.pdf
- Karabeyoglu et al, Scale-up Tests of High Regression Rate Liquifying Hybrid Rocket Fuels AIAA-2003-1162.pdf
- Karabeyoglu, Altman and Cantwell, Combustion of Liquefying Hybrid Propellants Part 1 General Theory JPP Vol 18 2002.pdf
- Karabeyoglu, Cantwell and Stevens, Evaluation of Homologous Series of Normal-Alkanes as Hybrid Rocket Fuels AIAA-2005-3908.pdf
- Karabeyoglu, Cantwell and Zilliac, Development of Scalable Space–Time Averaged Regression Rate Expressions for Hybrid Rockets JPP Vol 23 2007.pdf
- Karabeyoglu, Cantwell, Zilliac Development of Scalable Space–Time Averaged Regression Rate Expressions for Hybrid Rockets JPP Vol 23, 2007.pdf
- Karabeyoglu, De Zilwa, Cantwell, Zilliac Modeling of Hybrid Rocket Low Frequency Instabilities JPP Vol21 no6 2005.pdf
- Karabeyoglu, Dyer, Stevens and Cantwell, Modeling of N2O Decomposition Events AIAA 2008-4933.pdf
- Karabeyoglu, MA, Transient Combustion in Hybrid Rockets Stanford PhD thesis1998.pdf
- Lengelle et al, Combustion of Solid Propellants RTO-EN-023 2002.pdf
- MacDonald and Hughes, Solar Sailing Lectures 2004.pdf
- McGuire et al, Concept designs for NASA's Solar Electric Propulsion Technology Demonstration Mission AIAA 2014-3717.pdf
- Narsai, P., Nozzle Erosion in Hybrid Rocket Motors PhD thesis Stanford 2015.pdf
- NASA_Glenn_Reports
  - Gordon and McBride, Computer Program for Calculation of Complex Chemical Equilibrium NASA RP 1311 1994 Part I.pdf
  - McBride and Gordon, Computer Program for Calculation of Complex Chemical Equilibrium NASA RP 1311 1996 Part II.pdf
  - McBride, Zehe and Gordon, NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species 2002.pdf
- Nino and Razavi, Design of Two-Phase Injectors Using Analytical and Numerical Methods with Application to Hybrid Rockets 2019-4154.pdf
- NRC Vision and Voyages for Planetary Science in the Decade 2013 2022.pdf
- Rockets and Launch Vehicles_4.2.1_author?.pdf
- Tokaty, G.A. Soviet Rocket Technology 1963.pdf
- Tsiolkovsky, Exploration of the Universe with Reaction Machines 1898.pdf
- Zilliac and Karabeyoglu AIAA 2006-4504 Hybrid_Rocket_Fuel_Regression_Rate_Data_and_Modeling.pdf

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43 items, 1.05 TB available

Final List of Lectures/Topic areas and presenters − Jan 13 2020

1. 1/7/20 - Course Organization, Systems Overview, Chemical/Nuclear/Electric/Photonic – Cantwell
2. 1/9/20 - Review of Rocket Performance Parameters, Thrust, Impulse, Efficiency – Cantwell
3. 1/14/20 - Review of Thermodynamics and Chemistry – Karabeyoglu
4. 1/15/20 - Thermochemistry and Propellants, Part 1 – Karabeyoglu
5. 1/16/20 - Thermochemistry and Propellants, Part 2 – Karabeyoglu
6. 1/23/20 - Liquid Rocket Propulsion – Chang, Naik, Choudhary
7. 1/28/20 - Solid Rocket Propulsion – Haig, White, Kim, McKown
8. 1/30/20 - Launch/Mission Trajectories – Kim, Choudhary
9. 2/4/20 - Future Mission Concepts and Technology – Special lecture by Scott Hubbard
10. 2/6/20 - Launch Industry/Market – Crispie, Taraborrelli , White, McKown
11. 2/11/20 - Hybrid Rocket Propulsion Fundamentals – Haig, Korneyeva, Kehoe
12. 2/13/20 - Hybrid Rocket Propulsion Liquefying Fuels – Korneyeva, Haig, Crispie
13. 2/18/20 - Hybrid Rocket Propulsion Design Issues – White, Kim, Taraborrelli
14. 2/20/20 - Component Design Issues – Chang, White, Erhard
15. 2/25/20 - Stability of Chemical Rockets – Korneyeva, Finch, McClure
16. 2/27/20 - Rocket Testing – Kim, Haig, Erhard
17. 3/3/20 - MAV Design Study – Zilliac
18. 3/5/20 - Electric Propulsion – Kehoe, Taraborrelli, Erhard
19. 3/10/20 - Nuclear Propulsion – Choudhary, Taraborrelli, Korneyeva
20. 3/12/20 - Photonic Propulsion – Finch, Naik, Choudhary, McClure

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1. 1/7/20 - Course Organization, History, Systems Overview, Chemical/ Nuclear/Electric/Photonic

Resources

1. Clark, John D., *Ignition! An informal history of liquid rocket propellants, 1972*
2. Johnson, W., Contents and commentary on William Moore's *A treatise on the motion of rockets and an essay on naval gunnery, 1995*
3. Tsiolkovskiy, K.E., Exploration of the universe with reaction machines, 1898
4. Glushko, V.P., *Development of rocketry and space technology in the USSR,* 1973
5. Bilstein, R.E., Stages to Saturn A Technological History of the ApolloSaturn Launch Vehicles. NASA SP-4206, 1980
6. Hodapp, Martin, Germany's Rocket Development in World War II, 2013
7. Tokaty, G.A., Soviet Rocket Technology, 1963
8. Mieczkowski, Yanek, *Eisenhower's Sputnik Moment*, Cornell University Press, 2013
9. Jahn, R.,G. and Choueiri, E.Y., Electric Propulsion, in Encyclopedia of Physical Science and Technology, 3rd edition, Volume 5, 2002
10. Wright, J., *Space Sailing,* 1992
11. Hill, P. and Peterson, C., *Mechanics and Thermodynamics of Propulsion,* 1992 – Chapter 14
12. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements, 2010 – Chapter 17
13. Clarke, A.C., *Project Solar Sail,* 1990
14. Borowski, S.K., Corban, R.R, McGuire, Beke, E.,G., Nuclear Thermal Rocket/Vehicle Design Options for Future NASA Missions to the Moon and Mars, NASA TM 107071, AIAA-93-4170, 1993
15. Tummala et al., "An Overview of Cube-Satellite Propulsion Technology and Trends," 2017
16. Scott Manley's Youtube Channel https://www.youtube.com/channel/UCxzC4EngIsMrPmbm6Nxvb-A

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2. 1/9/20 − Review of Rocket Performance Parameters, Thrust, Impulse, Efficiency

Resources

1. Hill, P. and Peterson, C., *Mechanics and Thermodynamics of Propulsion,* 1992 – Chapters 10 and 11
2. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements, 2010 – Chapters 2, 3 and 5
3. Huzel, D.K. and Huang, D.H., *Modern Engineering for Design of Liquid-Propellant Rocket Engines*, Volume 147 Progress in Astronautics and Aeronautics AIAA, 1992 – Chapters 1, 2 and 3
4. Humble, R., Henry, G.N., and Larson, W.J.. *Space Propulsion Analysis and Design,* McGraw-Hill, Inc., 1995

3. 1/14/20 - Review of Thermodynamics and Chemistry − Arif Karabeyoglu

Resources

1. Glassman, I. and Yetter, R. *Combustion 2008 – Chapters 1, 2 and 3*
2. Hill, P. and Peterson, C., Mechanics and Thermodynamics of Propulsion 1992 – Chapter 12
3. Gordon, S. and McBride, B.J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications I – Analysis 1994
4. Gordon, S. and McBride, B.J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications II – Users Manual and Program Description 1996
5. McBride, B.J., Zehe, M.J. and Gordon, S., NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species 2002
6. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 – Chapter 5
7. Camberos, J.A. and Moubry, J.G., Chemical Equilibrium Analysis with the Method of Element Potentials AIAA paper 2001-873
8. Clasen, R.J., The Numerical Solution of the Chemical Equilibrium Problem, RAND Memorandum RM-4345-PR 1965

4. 1/15/20 - Thermochemistry and Propellants, Part 1 − Arif Karabeyoglu

Resources

1. Glassman, I. and Yetter, R. *Combustion 2008 − Chapters 1, 2 and 3*
2. Hill, P. and Peterson, C., Mechanics and Thermodynamics of Propulsion 1992 − Chapter 12
3. Gordon, S. and McBride, B.J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications I − Analysis 1994
4. Gordon, S. and McBride, B.J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications II − Users Manual and Program Description 1996
5. McBride, B.J., Zehe, M.J. and Gordon, S., NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species 2002
6. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 − Chapter 5
7. Camberos, J.A. and Moubry, J.G., Chemical Equilibrium Analysis with the Method of Element Potentials AIAA paper 2001-873
8. Clasen, R.J., The Numerical Solution of the Chemical Equilibrium Problem, RAND Memorandum RM-4345-PR 1965

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5. 1/16/20 - Thermochemistry and Propellants, Part 2

Resources

1. Glassman, I. and Yetter, R. *Combustion 2008 − Chapters 1, 2 and 3*
2. Hill, P. and Peterson, C., Mechanics and Thermodynamics of Propulsion 1992 − Chapter 12
3. Gordon, S. and McBride, B.J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications I − Analysis 1994
4. Gordon, S. and McBride, B.J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications II − Users Manual and Program Description 1996
5. McBride, B.J., Zehe, M.J. and Gordon, S., NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species 2002
6. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 − Chapter 5
7. Camberos, J.A. and Moubry, J.G., Chemical Equilibrium Analysis with the Method of Element Potentials AIAA paper 2001-873
8. Clasen, R.J., The Numerical Solution of the Chemical Equilibrium Problem, RAND Memorandum RM-4345-PR 1965

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6. 1/23/20 - Liquid Rocket Propulsion

Resources

1. Hill, P. and Peterson, C., Mechanics and Thermodynamics of Propulsion 1992 − Chapters 10, 11 and 12
2. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 − Chapters 6, 7, 8, and 9
3. Huzel, D.K. and Huang, D.H., Modern Engineering for Design of Liquid-Propellant Rocket Engines, Volume 147 Progress in Astronautics and Aeronautics AIAA 1992 − Chapters 1, 2 and 3
4. Humble, R., Henry, G.N., and Larson, W.J.. *Space Propulsion Analysis and Design,* McGraw-Hill, Inc., 1995
5. Yang, V. ed. Liquid Rocket Thrust Chambers: Aspects of Modeling, Analysis and Design, Volume 200 Progress in Astronautics and Aeronautics AIAA 2004 − Chapters 1, 2, 3 and 4
6. Davis S.M and, Yilmaz, N., "Advances in Hypergolic Propellants: Ignition, Hydrazine, and Hydrogen Peroxide Research," Advances in Aerospace Engineering, Volume 2014, Article ID 729313, 9 pages.

Suggested Themes

1. How have liquid rockets evolved since World War II? What have been the major advances?
2. Safety issues, accident history, history of launch failures.
3. Compare the Liquid Propulsion Systems developed by SpaceX, Blue Origin and the United Launch Alliance (Boeing/ Lockheed) and the European Space Agency.
4. What are the challenges to the future development of improved liquid systems in both the near and far term. Consider materials, performance, cost, manufacturing national needs, environmental issues.
5. What is the potential for additive manufacturing having an impact on future liquid propulsion systems?
6. What is the potential for green propellants?
7. Discuss the future heavy lift launch systems being developed by the US, Russia, China and India.

7. 1/28/20 - Solid Rocket Propulsion

Resources

1. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 – Chapters 12, 13, 14 and 15.
2. Hill, P. and Peterson, C., Mechanics and Thermodynamics of Propulsion 1992 – Chapter 12
3. Lengelle, G., Duterque, J.F., Trubert, J.F., Combustion of Solid Propellants, Paper presented at the RTO/VKI Special Course on "Internal Aerodynamics in Solid Rocket Propulsion", held in Rhode-Saint-Genèse, Belgium, 27-31 May 2002, and published in RTO-EN-023
4. Humble, R., Henry, G.N., and Larson, W.J.. *Space Propulsion Analysis and Design,* McGraw-Hill, Inc., 1995
5. Blount B.C., Pirkle, J.L., Osterloh, J.D., Valentin-Blasini, L., and Caldwell, K.L., Urinary Perchlorate and Thyroid Hormone Levels in Adolescent and Adult Men and Women Living in the United States, Environmental Health Perspectives, Vol 114, No. 12, 2006
6. NGIS Solid Propulsion Catalog https://www.northropgrumman.com/Capabilities/PropulsionSystems/Documents/NGIS_MotorCatalog.pdf

Suggested Themes

1. How have solid rockets evolved since World War II? What have been the major advances?
2. Safety issues, environmental issues, accident history.
3. Compare the solid boosters used by the United Launch Alliance (Boeing/Lockheed) and the European Space Agency.
4. What are the challenges to the future development of improved solid systems in both the near and far term. Consider materials, performance, cost, manufacturing national needs and especially environmental issues.
5. What is the potential for additive manufacturing having an impact on future solid propulsion systems?
6. What is the potential for green propellants?
7. Discuss solids in the context of the future heavy lift launch systems being developed by the US, Russia, China and India.

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8. 1/30/20 - Launch/Mission Trajectories

Resources

1. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 – Chapter 4
2. Wertz, J.R. and Larson, W.J., Space Mission Analysis and Design, Kluwer 1999 – Chapters 5, 6 and 7
3. Montenbruck, O. and Gill, E., Satellite Orbits: Models, Methods, Applications, Springer 2005
4. Bate et al., Fundamentals of Astrodynamics, 1971
5. Humble, R., Henry, G.N., and Larson, W.J.. *Space Propulsion Analysis and Design,* McGraw-Hill, Inc., 1995 - Chapter 2

Suggested Themes

1. Typical launch trajectories for suborbital launch, ballistic missiles, launch to LEO, GTO and GEO.
2. Uses for suborbital launch.
3. The problem of orbit maneuvering, on orbit servicing of spacecraft.
4. What is a fractionated satellite?
5. Crowding issues in GEO?
6. The orbital debris problem.
7. Orbital accuracy of solids versus liquids, orbital dispersion, energy management.

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10. 2/4/20 - Future Space Mission Concepts and Technology

Resources

1. Hubbard, S.H. Exploring Mars: Chronicles from a Decade of Discovery, University of Arizona Press 2012
2. Visions and Voyages for Planetary Science in the decade 2013 – 2022, National Research Council, The National Academies Press.
3. Visions into Voyages for Planetary Science in the decade 2013 – 2022: A MidTerm Review (2018), National Research Council, The National Academies Press.
4. Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration (2014), National Research Council, The National Academies Press.
5. Solar and Space Physics: A Science for a Technological Society (2013), National Research Council, The National Academies Press.
6. NASA's Strategic Direction and the Need for a National Consensus (2012) , National Research Council, The National Academies Press.

9. 2/6/20 - Launch Industry/Market

Resources

1. The Economics of Space: An Industry Ready to Launch, The Reason Foundation, June 2019.
2. Reusable Booster System: Review and Assessment (2012) , National Research Council, The National Academies Press.
3. America's Future in Space: Aligning the Civil Space Program with National Needs (2009), National Research Council, The National Academies Press.
4. Space Launch Services Market by Service Type (Pre-Launch, Post-Launch), Payload (Satellite, Human Spacecraft, Cargo, Testing Probes, Stratollite), End User, Orbit, Launch Vehicle Size, Launch Platform, and Region - Global Forecast to 2025, https://www.marketsandmarkets.com/Market-Reports/space-launch-services-market-132122845.html
5. Chang, I. and Tomei, E.J., Solid Rocket Failures in World Space Launches, AIAA paper 2005-3793.
6. Isakowitz, S. et al., International Reference Guide to Space Launch Systems, 4 ed. AIAA. 2004.

Suggested Themes

1. Is there a future for small launch vehicles/CubeSats?
2. Who are the dominant players in the launch industry in the US, Europe, Russia, China and India.
3. What other countries are developing launch vehicles and for what market?
4. Can government developed launch vehicles compete with private companies in the long term?
5. What new technologies are being developed in propulsion, manufacturing, systems integration, ground tracking?
6. Are launch failure rates getting any better?

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11. 2/11/20 - Hybrid Rocket Propulsion Fundamentals

Resources

1. Altman, D., Hybrid Rocket Development History, AIAA 91-2515, 27th Joint Propulsion Conference, Sacramento, 1991
2. Glushko, V.P., *Development of rocketry and space technology in the USSR,* 1973
3. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 – Chapter 16
4. Humble, R., Henry, G.N., and Larson, W.J.. *Space Propulsion Analysis and Design,* McGraw-Hill, Inc., 1995
5. Humble, R., Henry, G.N., and Larson, W.J.. Space Propulsion Education, AIAA 93-2048, 29th Joint Propulsion Conference, Monterey, CA 1993
6. Karabeyoglu, M. A., Transient Combustion in Hybrid Rockets, PhD thesis, Stanford University, 1998
7. D. Altman, A. Holzman, Overview and history of hybrid rocket propulsion, in: K. Kuo, M. Chiaverini (Eds.), *Fundamentals of Hybrid Rocket Combustion and Propulsion*, Vol. 218 of Progress in Astronautics and Aeronautics, AIAA, 2007, pp. 1–36.
8. H. S. Mukunda, V.K. Jain, and P.J. Paul, "A review of hybrid rockets: present status and future potential", Proc. Indian Acad. Sci., Vol C 2, part 1, May 1979, pp. 215-242.
9. Cantwell, B., Karabeyoglu, M.A. and Altman, D.A., Recent Advances in Hybrid Propulsion, International Journal of Energetic Materials and Chemical propulsion 9(4), 305-326 (2010)
10. *Chemical Rocket Propulsion: A Comprehensive Survey of Energetic Materials, Part VI Hybrid Rocket Propulsion*. L. De Luca, T. Shimada, V.P. Sinditskii, M. Calabro (Editors), Springer Aerospace Technology, 2017.
11. Zilliac, G.G. and Karabeyoglu, M.A., "Hybrid Rocket Fuel Regression Rate Data and Modeling," AIAA paper no 2006-4504, 42nd Joint Propulsion Conference, Sacramento, CA, July, 2006.
12. Karabeyoglu, M.A., Dyer, J., Stevens, J. and Cantwell, B.J., Modeling of N2O Decomposition Events, AIAA paper no 2008-4933, 44th Joint Propulsion Conference, Hartford, CT, July, 2008.

Suggested Themes

1. Discuss the history of hybrid rocket development, advantages and disadvantages versus solids and liquids, challenges to current technology development.
2. Summarize existing programs worldwide.
3. Safety issues, accident history, history of launch failures.
4. What is the status of hybrids applied to sub-orbital space tourism?
5. What role could hybrids play in future NASA space exploration, delta-V, safety, mission requirements.
6. Could hybrids replace solid boosters? What are performance, cost and safety issues.

12. 2/13/20 - Hybrid Rocket Propulsion Liquefying Fuels

Resources

1. Larson, C. W., Pfeil, K. L., DeRose, M. E., and Carric, P. G., "High Pressure Combustion of Cryogenic Solid Fuels for Hybrid Rockets," AIAA Paper 96-2594, July 1996.
2. Karabeyoglu, M.A., Transient Combustion in Hybrid Rockets, PhD thesis, Stanford University, 1998
3. Nigmatulin, R.I., Nigmatulin, B.I., Khodzhaev, D., Kroshilin, V.E., "Entrainment and Deposition Rates in a Dispersed-Film Flow" Int. J. Multiphase Flow, vol 22, 1996.
4. Karabeyoglu, M.A., Altman, D.A. and Cantwell, B.J., Combustion of Liquefying Hybrid Propellants: Part 1, General Theory, Journal of Propulsion and Power, Vol. 18, No. 3, 2002
5. Karabeyoglu, M.A., Altman, D.A. and Cantwell, B.J., Combustion of Liquefying Hybrid Propellants: Part 2, Stability of Liquid Films, Journal of Propulsion and Power, Vol. 18, No. 3, 2002
6. Karabeyoglu, M.A., Cantwell, B.J. and Stevens, J., Evaluation of Homologous Series of Normal-Alkanes as Hybrid Rocket Fuels, AIAA 2005-3908 , 41st Joint Propulsion Conference and Exhibit, 2005
7. Karabeyoglu, A., Zilliac, G. Cantwell, B., De Zilwa S. and Paul Castelluci, " Scale-Up Tests of High Regression Rate Paraffin-Based Hybrid Rocket Fuels", Journal of Propulsion and Power, Vol 20., No. 6, Nov-Dec, 2004.
8. Jens, E.T., Miller, V.A., Cantwell, B.J., "Schlieren and OH* Chemiluminescence Imaging of Combustion in a Turbulent Boundary Layer Over a Solid Fuel," Experiments in Fluids (2016) 57:39.
9. Jens, E.T., Karp, A.C., Miller, V.A., Hubbard, G.S., and Cantwell, B.J., "Experimental visualization of hybrid combustion: Results at elevated pressures," AIAA Journal of Propulsion and Power (2019) https://doi.org/10.2514/1.B37416
10. Chandler, A., Liquifying Hybrid Rocket Fuels with application to solar system exploration PhD thesis Stanford 2012

Suggested Themes

1. Applications where high regression rate fuels are needed or not needed, effect of scale on regression rate requirement.
2. Theory of liquifying fuels, model assumptions, stability theory, origins.
3. Instabilities in hybrids.
4. How are hybrid fuels characterized? What is a Differential Scanning Calorimeter and how is it used? What is a Thermogravimetric Analyzer and how is it used?

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13. 2/18/20 - Hybrid Rocket Propulsion Design Issues

Resources

1. Karabeyoglu, M.A., Cantwell, B.J., Zilliac, G., Development of Scalable Space-Time Averaged Regression Rate Expressions for Hybrid Rockets, Journal of Propulsion and Power, Vol. 23, No. 4, 2007
2. Jens, B., Hybrid Rocket Combustion and Applications to Space Exploration Missions, PhD thesis, Stanford University 2015 − Chapter 3
3. Mechentel, F., Preliminary Design of a Hybrid Motor for Small-Satellite Propulsion, PhD thesis, Stanford University 2019 − Chapters 1 and 2
4. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 – Chapters 16.

Suggested Themes

1. How are hybrid rocket motors tested.
2. Theory of liquifying fuels, model assumptions, stability theory, origins.
3. Instabilities in hybrids.
4. How are hybrid fuels characterized? What is a Differential Scanning Calorimeter and how is it used? What is a Thermogravimetric Analyzer and how is it used?

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14. 2/20/20 - Component Design Issues

Resources

1. Sutton, G.S. and Biblarz, O., *Rocket Propulsion Elements* 2010 – Chapters 6, 8, 10, and 11
2. Huzel, D.K. and Huang, D.H., *Modern Engineering for Design of Liquid-Propellant Rocket Engines*, Volume 147 Progress in Astronautics and Aeronautics AIAA 1992
3. Zhukov, Victor P., "The impact of methane oxidation kinetics on a rocket nozzle flow," Acta Astronautica, Vol. 161, August 2019, Pages 524-530.
4. Manski, D., and Hagemann, G., ''Influence of Rocket Design Parameters on Engine Nozzle Efficiencies,'' Journal of Propulsion and Power, Vol. 12, No. 1, 1996, pp. 41– 47.
5. Östlund, J., "Flow Processes in Rocket Engine Nozzles with Focus On Flow Separation and Side-Loads," Thesis 2002.
6. "Solid Rocket Motor Nozzles," NASA SP-8115, June 1975.
7. "Solid Rocket Motor Internal Insulation," NASA SP-8093, Dec. 1976.
8. "Solid Rocket Motor Metal Cases," NASA SP-8025, April 1970.
9. "Discontinuity Stresses in Metallic Pressure Vessels," NASA SP-8083, Nov. 1971
10. Space Systems-Metallic Pressure Vessels, Pressurized Structures and Pressure Components," Standard ANSI/AIAA S-080-1998.
11. Space Systems-Composite Overwrapped Pressure Vessels, (COPVs) Standard ANSI/AIAA S-081-2000.
12. Nino, E.V. and Razavi, M.R., Design of Two-Phase Injectors Using Analytical and Numerical Methods with Application to Hybrid Rockets, AIAA 2019-4154
13. Waxman, B., PhD thesis Stanford 2014.
14. Zimmerman, J., Self-pressuring propellant tank dynamics PhD thesis Stanford 2015.
15. Narsai, P., Nozzle Erosion in Hybrid Rocket Motors PhD thesis Stanford 2015

Suggested Themes

1. Compatibility issues between common oxidizers/fuels and composite materials.
2. What is the current status of composite vessels for cryogenic liquids.
3. Discuss tank design in general and tank design for high vapor pressure liquids, the problem of expelling liquid from a tank.
4. Discuss injector design and operation, atomization, mixing, feed-coupled instability.
5. Discuss the problem on rocket nozzle erosion.

15. 2/25/20 - Stability of Chemical Rockets

Resources

1. Sutton, G.S. and Biblarz, O., *Rocket Propulsion Elements* 2010 – Chapter 9
2. Culick, F.E.C., Combustion Instabilities in Liquid-Fueled Propulsion Systems – An Overview, AGARD Conference Proceedings 450, 1988
3. Culick, F.E.C. and Yang, V., Prediction of the Stability of Unsteady Motions in Solid-Propellant Rocket Motors, In *Nonsteady Burning and Combustion Stability of Solid Propellants*, Summerfield, M., Price, E.W. and De Luca, L., AIAA 1992
4. Karabeyoglu, M.A., De Zilwa, S., Cantwell, B.J. and Zilliac, G., Modeling of Hybrid Rocket Low Frequency Instabilities, Journal of Propulsion and Power, Vol. 21, No. 6, 2005
5. Karabeyoglu, M.A., Stability of Chemical Rockets, AA284A Lecture 14.

Suggested Themes

1. Classify rocket motor instabilities with respect to driving mechanism and propulsion type, liquid, solid, hybrid.
2. Summary of theoretical approaches to rocket motor stability analysis.

16. 2/27/20 - Rocket Testing

Resources

1. Sutton, G.S. and Biblarz, O., *Rocket Propulsion Elements* 2010 – Chapters 21.

Suggested Themes

1. Testing techniques, the problem of measuring thrust.
2. How does sea level testing impact measured performance?
3. What are the different ways to measure oxidizer and fuel mass flow rate?
4. Any advantages/considerations to ground test article orientation?
5. What are the essential measurements required to evaluate performance?

17. 3/3/20 - MAV Design Study

Resources

1. Prince, A., Kibbey, T., Karp, A., A Design for a Two-Stage Solid Mars Ascent Vehicle, AIAA 2019-4149, AIAA Propulsion and Energy Forum, Indianapolis, 2019
2. Story, G., Schnell, A., Yaghoubi, D., Karp, A., Nakazono, B., Zilliac, G., A Single Stage to Orbit for a Hybrid Mars Ascent Vehicle, AIAA 2019-3840, AIAA Propulsion and Energy Forum, Indianapolis, 2019

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18. 3/5/20 - Electric Propulsion

Resources

1. McGuire, M.L., Hack, K.J., Manzella, D.H., Herman, D.A., Concept designs for NASA's Solar Electric Propulsion Technology Demonstration Mission, AIAA paper 2014-3717
2. Jahn, R.,G. and Choueiri, E.Y., Electric Propulsion, in Encyclopedia of Physical Science and Technology, 3rd edition, Volume 5, 2002
3. Journal of Propulsion and Power, Vol 14, No. 6, 1998 − Includes review papers on Electric Propulsion, Ion thrusters, Hall Thrusters, arcjets, etc.
4. Hill, P. and Peterson, C., Mechanics and Thermodynamics of Propulsion 1992 − Chapter 14
5. Sutton, G.S. and Biblarz, O., Rocket Propulsion Elements 2010 − Chapter 17

Suggested Themes

1. Power types and limitations, solar, nuclear.
2. Durability of electric thrusters.
3. Missions needing electric propulsion
4. Impact of low thrust on applicability to missions?

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19. 3/10/20 - Nuclear Rocket Propulsion

Resources

1. Borowski, S.K., Corban, R.R, McGuire, Beke, E.,G., Nuclear Thermal Rocket/Vehicle Design Options for Future NASA Missions to the Moon and Mars, NASA TM 107071, AIAA-93-4170 1993

Suggested Themes

1. Power types and limitations.
2. Missions best suited for nuclear propulsion.
3. Does nuclear have a future?
4. The radioisotope rocket.
5. High energy particle engines.

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20. 3/12/20 – Photonic Propulsion

Resources

1. McGuire, M.L., Hack, K.J., Manzella, D.H., Herman, D.A., Concept designs for NASA's Solar Electric Propulsion Technology Demonstration Mission, AIAA paper 2014-3717
2. Wright, J., Space Sailing 1992
3. Macdonald and Hughes, Solar Sailing Lectures 2004
4. Clarke, A.C., Project Solar Sail 1990
5. McInness, C.R., Solar Sailing 1999

Suggested Themes

1. Latest sail technologies.
2. Mission successes and failures
3. Define a practical mission to demonstrate laser based solar sail technology.

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Topic/theme proposals for each student

Efaine Chang

Topic 1: Liquid Propulsion

On the subject of liquid rocket propulsion, I aim to briefly discuss current technologies i.e. SpaceX, ULA, etc. selections, and then launch into a discussion on various heavy launch systems in development globally. Along this vein, I will present on various challenges encountered in the development process including material and manufacturing selection. I hope to wrap up discussion by touching on the promise of more recent advancements such as additive manufacturing.

Topic 2: Component Design Issues

For component design issues, I aim to focus on the thrust chamber assembly. Specifically, I will skim over the basic operation and current configurations of the combustion chamber, and then home in on combustion instability. On this, I will discuss injector elements and design for performance, cost and stability. To conclude, and to provide some application, I will touch on injector design in the F-1 Engines from Saturn V.

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Rishav Choudhary

Propulsion systems for Single Stage To Orbit (SSTO) vehicles

The quest for routine, reliable, and affordable means of launching payloads into the low-Earth orbit (LEO) was the driving force behind the development of the Space Shuttle by NASA, and more recently, Reusable Launch Vehicles (RLVs) by SpaceX and Blue Origin. While SpaceX RLVs have managed to bring the cost, per pound to orbit, down to $2500, the rather long turnaround time (~2 months) between two successive launches is debilitating. SSTO launch vehicles can provide a possible solution to this by combining the recent advances in the field of hypersonic air-breathing propulsion with the conventional rocket propulsion systems. The presentation will be centered around the propulsion system configurations that are being considered for SSTOs. Most of these systems are built around Rocked Based Combined Cycles (RBCCs), which integrate a dual-mode scramjet with rocket boosters. The operating envelope, theoretical performance parameters, variants of the thermodynamic cycle, challenges, and exploratory programs undertaken by different space agencies will be discussed.

Interplanetary Trajectories

The choice of trajectories for an interplanetary mission is contingent on the propellant consumption that it will entail. The trajectories that consume the least amount of propellants are of interest. Depending on the limitations of the onboard propulsion system, mass of the spacecraft, the power of the launch vehicle used and the orbit/orbital velocity of the target planet/satellite/asteroid, the trajectory pursued by the spacecraft can involve multiple orbit changes, gravitational slingshot, or a combination of both. Every orbit change and orbit correction maneuvers require a Δv, provided by the propulsion systems on the spacecraft, which can either be a chemical rocket with a short burn time, or an ionic propulsion system. The presentation will discuss some case studies (e.g. Comparison of trajectories of NASA's MAVEN, and ISRO's Mars Orbiter Mission, Cassini, Voyager-1 & 2, JAXA's Hayabusa 2 etc.) The characteristics of the propulsion systems used onboard each of these missions will be discussed in the light of the trajectories chosen.

Overview of Nuclear Propulsion Systems & development of Low-Enriched Uranium (LEU) based rocket engines

The first half of the presentation will focus on the key aspects of the engines designed under the NERVA program. The design considerations, including the choice of the thermodynamic cycle, design and control of the nuclear reactor, shielding techniques, turbopump and nozzle design will be discussed. The issues with ground testing of rocket engines powered by highly enriched uranium-based reactors will also be discussed. The second half of the presentation will focus on the recent feasibility studies of LEU based rocket engines, proposed thermodynamic cycles, candidate materials for fuel and moderator, and development of facilities for ground testing of these engines.

Advanced solar sailing mission concepts and associated technological challenges

The presentation will be centered towards three advanced concept missions that will be enabled by advancement in solar sail technologies; ESA's solar polar mission, a solar storm monitoring mission, and interstellar probe. The solar polar mission aims to place a spacecraft in a polar heliocentric orbit, which is prohibitive using only chemical propulsion. The proposed mission will attempt to achieve a heliocentric orbit at an inclination of 34 degrees using gravity assist and conventional chemical propulsion. Solar sail propulsion will subsequently raise the inclination to ~83 degrees and will enable observation of the poles of the Sun without any planetary flybys. The solar storm monitoring mission's objective is to place a solar sail powered probe sunward of the Lagrangian point L1, which will enable early warning of solar storms. The interstellar probe mission intends to use solar sailing to achieve heliocentric escape velocity. Each of these missions require a sail area that is roughly two orders of magnitude greater than the largest sail that has been deployed to date (IKAROS ~ 196 m^2). The technological advancements needed to enable these missions will also be a part of the presentation.

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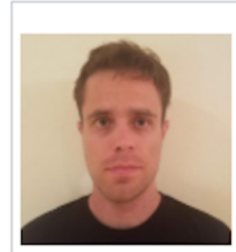
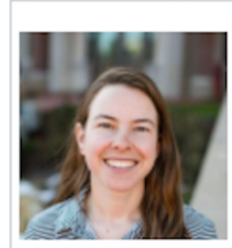
Kevin Crispie



Space Launch Industry
For this topic, I'll focus on launch industry failures, mostly focused on propulsion failures, and discuss the responses to those failures. I'll target a few different design anecdotes, likely one surrounding the early days of the space program, as well as discussing the Space Shuttle program's approach to failure as well as the private launch industry's approach to failure for comparison. I'll treat the examples as case studies of what went wrong with the design and what solutions were taken to fix it. To limit the scope of the report, I'll avoid diving deep into any organizational problems and mostly focus on propulsion failures and problems that have not been discussed at much length. Examples that I think I'll cover are the early failures of US rockets, the Soviet N1 project, Apollo 13, and the SpaceShipOne hybrid rocket test failure. I'll also plan on including information about testing of rocket engines in the early Apollo era, with the instabilities of the F-1 engine that were eventually successfully solved.

Liquefying Hybrid Fuels
My topic will be focused primarily on the modeling and theory of liquifying fuels, with some discussion on the applications of liquefied hybrid fuels and what improvements are necessary to utilize the technology in future space missions. I plan to begin the report and lesson by discussing the advantages of liquefying hybrid fuels, namely focusing on increased regression rates over a more traditional, non-liquefied fuel hybrid. I'll then explore the theoretical model of liquefied fuel, using this to explain the advantages. This type of fuel has benefits and applications from a rocket/mission design perspective, and I plan on ending the report and lesson detailing the limitations of the technology, leveraging the exploration of the theory done previously as well as some practical considerations for the technology.

Racheal Erhard



Topic 1: Component Design Issues (Presenting on 2/20)

Title of Theme: "What is the current status of composite vessels for cryogenic liquids?"

In this topic, I will discuss the current status of composite vessels for cryogenic liquids. There has been a push for developing lightweight pressure vessels capable of handling cryogenic liquids while staying cost effective and not sacrificing strength of the vessel. Concerns of using composites for such a task include microcracking of composite laminates subjected to extremely cold environments, which may lead to leaks in the vessel. Such microcracking is possible in all laminates, and is caused by the difference in axial and transverse coefficients of thermal expansion (CTE) in each ply. A paper by Atli-Veltin discusses one solution to reduce microcracking by the use of Single Polymer Composites (SPCs), which have the advantage of adhesion between the amorphous matrix and the semicrystalline reinforcement [1]. Having similar constituent materials also results in CTE values much closer together, reducing the difference in expansion and contraction during thermal cycles. This helps reduce microcracking in the composites. Through the in class presentation, I will discuss and expand on these topics, further discussing the current status of composite vessels for cryogenic liquids.

Topic 2: Rocket Testing (Presenting on 2/27)

Title of Theme: "How does sea level testing impact measured performance?"

Sea level testing is an important first step before launch, providing comparatively inexpensive testing results. However, although sea level testing helps understand start characteristics for ground-launched rockets, it fails to capture a true simulation of the rocket performance at high altitude. Through ground testing, many important aspects can be measured and verified, including sea level thrust, but since the atmosphere is not as thin as what the rocket is designed for, performance for high altitude mission segments is not accurately measured. Rocket engines typically use high expansion ratio nozzles to increase performance. When operated at sea-level, the ambient pressure is much higher than what the rocket is designed for. This results in flow separation from the nozzle wall, effectively reducing the thrust [2]. The effect of lower air pressure at higher altitudes results in higher rocket thrust and lower heat transfer. Therefore, the sea-level testing will under-predict thrust and over predict heat transfer. Depending on the type of rocket engine, there are other considerations that must be taken into account as well. For liquid rocket engines, the effect of propellant weight must be accounted for in the thrust measurement system (TMS). On the other hand, solid rocket engines do not need to account for the changing weight of the rocket in the TMS when launched in a horizontal position. The ignition characteristics are also important to consider; solid rocket motors at sea level may ignite without issues, but may have insufficient pressure to ignite when at altitude. All of these points are important to consider when evaluating the performance of a rocket based on sea-level test results. These points will be addressed in my lecture on this topic.

Peter Finch

Stability of Chemical Rockets

The theme I would like to pursue within this subject is the various control schemes that have been employed historically to combat instabilities, as well as look at potential novel schemes. The most common passive control methodology is through the use of baffles, which interfere strongly with the establishment of tangential (spinning) modes. The number of blades depends on the types of modes that can be established in the combustor, and more recently asymmetric baffles have also been explored. Other passive techniques include strategically choosing injector geometries and spray characteristics to emulate a baffle, as well as the use of acoustic resonators to siphon energy at certain frequencies. Active control techniques include modulating fuel line delivery at either frequencies detuned from the principal modes of oscillation or, with greater complexity, at the target frequencies but dephased. In addition to combustion instabilities, couplings between thrust and the structural modes of the rocket can also produce low frequency 'POGO' Oscillations, which historically have been of great interest. Passive techniques to combat this problem include prefilling feed lines. Solutions to instabilities come with different benefits and drawbacks, and these will be compared.

Photonic Propulsion

The theme I would like to pursue within this subject is an analysis of previous missions that have employed solar radiation pressure, as well as an investigation of future mission proposals. The survey of previous missions will range from true solar sails, like the JAXA IKAROS and the NASA NanoSail, to the use of solar pressure as an auxiliary control scheme such as in the MESSENGER and Kepler K2 missions. I will also describe current efforts by the Planetary Society to operate their Lightsail missions. Future mission concepts include NEA (Near Earth Asteroid) Scout, a NASA mission secondary payload on Artemis 1, and the IKAROS successor, the OKEANOS. By exploring mission concepts, I would like to shed light on why solar sail technology has suffered as a primary propulsive option within the trade space, but has greater potential when utilized in concert with other technologies.

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Bernadette Haig

I. Solid Rocket Propulsion

The safety issues with solid rocket boosters (SRBs), including environmental concerns and accident history, are discussed. Negative consequences of solid rocket manufacture include environmental contamination from propellant (commonly, ammonium perchlorate). When perchlorate enters the environment, it easily contaminates drinking water and crops. [1] Human ingestion of perchlorate has been linked to inhibited thyroid function. Specifically, perchlorate appears to interfere with iodide uptake, especially in women. [1]

One major drawback of solid rocket motors is that once ignited, they cannot be shut down. The most high-profile incident involving the failure of an SRB was the Space Shuttle Challenger accident in 1986. Due to brittle O-rings and a poorly designed joint, hot gas from the burning booster was able to leak out from the right SRB. The flame impinged on the strut connecting the booster to the External Tank (ET), burning through the strut and causing the booster to impact the ET. The tank exploded almost immediately. During this part of the launch (while the SRBs were thrusting), there were no survivable abort options. [2]

II. Hybrid Rocket Propulsion: Fundamentals

The advent of space tourism has created a new market for hybrid rocket propulsion. Many companies, including Airbus, Boeing, Blue Origin, and Virgin Galactic, plan to sell suborbital flights. [3] Hybrid rockets are inherently safer than both solid and liquid rockets because they store their fuel and oxidizer in different physical states (solid and gaseous or liquid, respectively). This is a mechanically safe design which which nevertheless drastically reduces the risk of accidental ignition. Furthermore, unlike solid rockets, hybrids can be throttled and restarted. [3]

In December 2018, Virgin Galactic successfully launched its *VSS Unity* vehicle on its first suborbital flight, with two pilots on board. The vehicle took off on a carrier aircraft, and then separated and used a *RocketMotorTwo* hybrid rocket to reach space. The 60,000 *lbf* motor burned for one minute and accelerated the vehicle to Mach 2.9 and a peak altitude of 51.4 miles. [4] This motor was developed in-house by Virgin Galactic and uses hydroxyl-terminated polybutadiene (HTPB) as its fuel and nitrous oxide for its oxidizer. [5]

III. Hybrid Rocket Propulsion: Liquefying Fuels

A major drawback of conventional hybrid rockets is their low fuel regression rate. This characteristic correlates to poor fuel loading and low thrust densities. The issue may be mitigated by designing a complex grain with multiple fuel ports; however, the tradeoffs include larger residuals and compromised grain integrity. [6] On the other hand, propellants which form a melt layer at the combustion surface have been found to have significantly higher fuel regression rates. For example, in experiments conducted at Stanford with a paraffin wax-fueled laboratory-scale hybrid motor, regression rates 3-4 times higher than HPTB (a conventional hybrid fuel) were observed. [7]

Furthermore, it has been shown that the high regression rate observed in the laboratory motors scales up with larger hybrids, at chamber pressures and mass fluxes consistent with operational systems. [7] The regression rate data from the large motors has also been found to match well to the small ones, validating small laboratory-scale motors as a useful tool for developing propellant characteristics. Importantly, the regression rate was also unaffected by any length or pressure effect in the larger motors. [7]

IV. Rocket Testing

The implications of sea level testing and ground test article orientation are discussed. It is convenient to test at sea level (with the rocket on the ground, as opposed to at altitude) and can be a useful indicator of performance during the beginning of a ground launch. [8] However, testing at sea level imposes conditions on the rocket that usually do not match those of flight. Liquid engines might experience an ignition delay in flight caused by vaporization and cooling of propellants, a condition which might not occur when testing at sea level. [9] A solid motor might ignite reliably at sea level but not achieve sufficient pressure for ignition in a vacuum. [9] In May 2019, Northrop Grumman Innovation Systems static tested the first stage of their OmegA booster. The nozzle broke apart during tail-off (at which point the vehicle would be high in the atmosphere in flight) due to a condition that they failed to consider for testing on the ground.

Typical sea level test stands are designed to restrain a rocket in either a horizontal or vertical position. Liquid rockets are normally tested vertically because the propellant pump intakes are designed to draw from the bottom of the tanks. However, this configuration requires the effect of the propellant weight on the thrust management system (TMS) to be considered. [8] A vertical test stand directs the rocket exhaust into a flame bucket or trench, which redirects it safely. Solid rockets may be tested vertically or horizontally; one advantage of testing horizontally is that the TMS system does not need to account for the changing weight of the rocket. [8]

References

[1] Blount, B. C., Pirkle, J. L., Osterloh, J. D., Valentin-Blasini, L., and Caldwell, K. L., "Urinary Perchlorate and Thyroid Hormone Levels in Adolescent and Adult Men and Women Living in the United States," *Environmental Health Perspectives*, Vol. 114, No. 12, 2006, pp. 1865–1871. doi:10.1289/ehp.9466.

[2] Rogers, W. P., Armstrong, N. A., Acheson, D. C., Covert, E. E., Feynman, R. P., Hotz, R. B., Kutyna, D. J., Ride, S. K., Rummel, R. W., Sutter, J. F., Walker Jr., A. B. C., Wheelon, A. D., and Yeager, C. E., "Report to the President by the Presidential Commission on the Space Shuttle Challenger Accident," June 1986.

[3] Cantwell, B. J., "Wax Fuel Gives Hybrid Rockets More Oomph," `https://spectrum.ieee.org/aerospace/space-flight/wax-fuel-gives-hybrid-rockets-more-oomph`, November 2014.

[4] Smithsonian, "Virgin Galactic Rocket Motor Joins Air and Space Collection," `https://airandspace.si.edu/stories/editorial/virgin-galactic-rocket-motor-joins-air-and-space-collection`, February 2019.

[5] White, A., "The Engine Powering the Future of Civilian Spaceflight Enters the Collections," `https://www.smithsonianmag.com/smithsonian-institution/engine-powering-future-civilian-spaceflight-enters-collections-180971493/`, February 2019.

[6] Karabeyoglu, M. A., Altman, D., and Cantwell, B. J., "Combustion of Liquefying Hybrid Propellants: Part 1, General Theory," *Journal of Propulsion and Power*, Vol. 18, No. 3, 2002, pp. 610–620.

[7] Karabeyoğlu, A., Zilliac, G., Cantwell, B. J., DeZilwa, S., and Castellucci, P., "Scale-Up Tests of High Regression Rate Paraffin-Based Hybrid Rocket Fuels," *Journal of Propulsion and Power*, Vol. 20, No. 6, 2004, pp. 1037–1045. doi:10.2514/1.3340.

[8] Wikipedia, "Rocket engine test facility," `https://en.wikipedia.org/wiki/Rocket_engine_test_facility`, January 2020.

[9] NASA, "Why Test at Simulated Altitude Conditions?" `https://www.nasa.gov/centers/wstf/pdf/271540main_2why_test_at_simulation_alt_cond_prop.pdf`, January 2020.

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Walker Kehoe

Hybrid Rocket Propulsion Fundamentals (2/11)
I'd like to do a survey of some of the most notable past and current hybrid rockets to talk about why some of them worked and some of them didn't. Hopefully this "case study" format will lead to valuable takeaways for students in 284B who are developing hybrids. Rockets I plan on including are: Peregrine, HYSER, SpaceShipTwo, Dream Chaser, Norway Nucleus. I plan on setting up a time to interview Greg for some firsthand knowledge on the projects that he's worked on.

Electric Propulsion (3/5)
I'd like to research and present on the microwave electrothermal thruster (MET). It's a technology that was originally proposed in the 1960s but that is only now being developed for commercial space applications. There are compelling reasons to use the MET over other in-space propulsion technologies, both from a cost and reliability standpoint. I plan on describing the technology and comparing it against other in-space propulsion options currently on the market.

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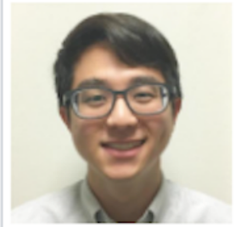
Andrew Kim



For the topic of Solid Rocket Propulsion, I will research and present on the advances in solid rocket technology since World War II. I will look at modern developments in the following areas: fuel, manufacturing processes, producers, users, and ongoing research.

For the topic of Launch/Mission Trajectories, I will research and present on the issue of orbital debris. I will address the following areas: history, sources, hazards posed, tracking methods, and current efforts for mitigating growth and spacecraft collisions.

For the topic of Hybrid Rocket Propulsion Design Issues, I will present on how hybrid fuels are characterized, using various common fuels as examples, and discuss differential scanning calorimeters and thermo-gravimetric analyzers.

For the topic of Rocket Testing, I will focus on the essential measurements required to evaluate performance. I will address performance measurements such as those involving forces, flows, pressures, and temperatures, how they are generally measured, and why they are relevant.

Veronika Korneyeva

1. Hybrid Rocket Propulsion Fundamentals

Role of hybrid rockets in future NASA space exploration missions. Brief review of the benefits vs downsides of using hybrids over more conventional propulsion systems for exploration missions. A discussion of the competition to use hybrid or solid propulsion for the Mars Ascent vehicle. Considerations to take into account for bolstering the competitive value of hybrids for future missions such as regression rates, alternative ignition, and combustion instabilities. Since the next session will involve my discussion of instabilities in hybrid rockets, the latter feels like an appropriate transition topic.

2. Hybrid Rocket Liquefying Fuels

Instabilities in hybrid rocket motors (acoustic and non-acoustic). Discussion of the modes of instabilities in hybrids including the phenomena and where they are typically located. A review of the combustion process in hybrid rockets as well as a visualization of the flame holding instability phenomenon. Review of the issues caused by these instabilities as well as successful efforts to rectify them such as changing the injection scheme, introducing recirculation zones, and having a constant pilot flame. Why efforts in quantifying instabilities are important: instabilities are dealt with as they appear in development. The necessity of better models to predict instabilities in hybrid designs and some approaches to achieving them.

3. Stability of Chemical Rockets

Summary of approaches to stability analysis. Brief commentary on the types of instabilities prevalent in liquids (injection processes), solids (acoustic waves), and hybrids (low frequency oscillation). General analysis methods: Liquids: numerical approach in CFD analysis, energy corollary method (time lag theory). Hybrids: oscillation frequency estimation, thermal combustion coupled model. Solids: simplified equations of conservation, acoustic wave theory. Overlap between all combustion systems: acoustic modeling, numerical resolution of non-linear equations, combination of analytical and numerical methods, linear solution for a first order approximation of onset/growth of instability.

4. Nuclear Propulsion

Discussion of missions best suited for nuclear propulsion.

- Use of a radioisotope thermal rocket engine (Triton Hopper) to explore Neptune's moon. Concept was to use in-situ propellent (Nitrogen) and heat it via the nuclear system. Decreased propellant mass.
- Use of low enriched uranium fuel to heat cryogenic hydrogen propellent for human exploration missions to Mars and the Moon. Improvement in specific impulse over chemical rockets and shortened travel duration.
- Nuclear electric propulsion systems for robotic solar system and deep space missions – Prometheus Project. Higher thrust electric propulsion systems – SPEAR probe to Europa. Reduced propellant mass and decoupling of propellent from energy source.

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Thomas McClure

Design for Stability of Liquid Propellant Rockets

Design features for stability control in liquid propellant rocket engines; Overview of causal links observed between certain design features and stability behavior of engine systems; High-frequency oscillatory behavior, which tends to be the most destructive. Design features addressed will include manifold flow, injector orifice/jet profile, baffling, and particulate inclusion; Overview of the instability mitigation efforts pursued in the development of the F-1 engine for the Apollo program; Low- and mid-frequency oscillation and "pogo" will be addressed, along with the associated feed system modifications used for damping; High-level description of methods used to predict the effects of design changes on stability; Presentation will ideally provide an understanding of propulsion system instability relevant to the various liquid-propellant engines currently being commercially developed.

Photonic Propulsion Project Topic

I want to evaluate the feasibility of a mission to Alpha Centauri using laser based solar sail technology. The mission will not necessarily depend on the use of current lasers or sail technology and may rely on future developments in both fields. The project will develop specifications for a laser to be used, including its power consumption, wavelength, and upper limits for beam divergence. Several base locations for the laser will be considered including the Earth's surface, the moon, and other bodies in the solar system. The possibility of staging the laser may be considered, by which I mean launching additional spacecraft with lasers on-board after the initial spacecraft leaves. The secondary spacecraft would then be able to provide thrust to the spacecraft with the mission payload from a shorter distance, which could help deal with beam divergence. The mission may still include chemical propulsion or ion thrusters for maneuvering and slowing down at Alpha Centauri. The solar sail area requirement will be calculated for a given payload mass and the total mission time will be considered.

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Quincy McKown

Green Solid Propulsion

The world is currently in crisis. The rising global temperatures will have monstrous effects on our planet in the coming years and efforts to curb this must be on the forefront of all engineers' minds. Solid rocket propulsion using the oxidizer ammonium perchlorate yields by-products that are water vapor, carbon dioxide, and hydrochloric acid. Hydrochloric acid is known to deplete the ozone layer and cause acid rain. Green oxidizers, or those that minimize environmental and toxicological hazards, have been studied as alternatives to the dominantly used ammonium perchlorate. An investigation into these alternatives and their feasibility for future use will be conducted in the research.

Resources:

- How Much Air Pollution is Produced by Rockets? by Leonard David, SPACE.com, November 2017
- The Coming Surge of Rocket Emissions by Martin Ross and Darin Toohey, September 2019
- Recent advances in new oxidizers for solid rocket propulsion by Trache, et. al, Green Chemistry, 2017
- http://www.scielo.br/pdf/jatm/v5n2/2175-9146-jatm-05-02-0139.pdf

Launch Industry/Market

The high financial and personnel cost of getting to space has forced the space market to be dominated by government agencies, namely in the US, Europe, Russia, China, and India, or behemoth public conglomerates like Lockheed Martin and Boeing (currently operating into space as the United Launch Alliance). Beyond that, SpaceX, Blue Origin, and Virgin Galactic are private companies who are currently seeking to force their way into the business with technical prowess, low cost, and luxurious promises for commercial use. An investigation how these companies' presence has the power to completely alter how we access space and what it means for competitors will be conducted in the research.

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Ashkay Naik

<u>Liquid Rocket Propulsion Topic:</u>

I will be presenting on the <u>propellant types used in liquid fuel rockets</u>. I plan to cover the progression of the technology, including performance, the story behind the development of the technology, and a comparison between the use of different fuels for different missions and flight regimes. The presentation and paper will describe technology spanning from the early beginnings to future liquid fuel-based rocket designs, with some description of their applications. I will be focusing specifically on the different propellant combinations and their uses, however.

<u>Photonic Propulsion Topic:</u>

As there is a scarcity in information available for this topic, I will discuss mission successes and failures, along with possible other applications for different solar sail technologies (such as laser-based solar sail technology). I currently have some ideas about deep space missions, but will require further research to develop them.

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Alec Taraborrelli

Launch Industry / Market: 2/6/20

What other countries are developing launch vehicles, different strategies of these companies including what market and type of launch vehicle is being utilized. Where is rocket launch occurring, and why? Including how government policy has affected launch startup success. I will also hopefully build upon the launch/mission trajectories lectures on 1/30.

Hybrid Rocket Design Issues: 2/18/20

For my lecture on hybrid rocket design issues I will focus on an overview of fuel grain port structures. I will reference many different attempts to change port structures, including the ideas behind the design and the methods of characterizing their success.

https://arc.aiaa.org/doi/pdfplus/10.2514/1.B35615

Electric Propulsion: 3/5/20

For my lecture on electric propulsion I would like to focus on the new air breathing electric propulsion technologies. I will start with an overview of the ion thruster and hall effect thruster. Including their current applications and drawbacks. I will then introduce the new technology in which air replaces xenon as the propellant. I will speak on different approaches to this propellant change. I will also talk about how have these advancements have changed the applications of ion thrusters and opened new areas of research? I will conclude with drawbacks and areas of improvement for the thrusters.

https://futurism.com/esa-ion-thruster-breathes-air

https://sci.esa.int/web/smart-1/-/34201-electric-spacecraft-propulsion

https://www.nature.com/articles/s41586-018-0707-9

Nuclear Propulsion: 3/10/20

For my lecture on nuclear propulsion I will ask the question does nuclear have a future? I will begin with a brief overview of the history and discuss why nuclear propulsion has failed to gain traction? I will then go over the projected next steps of the industry including scientific breakthroughs that could solve nuclear’ s problem.

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Thomas White

Solid Rocket Motors:
This project will investigate the behavior of solid propellants, including, but not limited to, Ammonium Perchlorate, in the presence of temperature and pressure changes. The discussion will begin with an overview of the ignition properties of solid propellants and what affects them, how low pressure affects ignition, and how it is resolved, especially when high-altitude ignition (such as staging) is involved. It will then move onto the affects of temperature and pressure on grains themselves, including glass transition and burn rate. If possible, the presentation will be augmented with experimental results from SSI's motor characterization efforts.

Industry/Market:

This presentation will estimate the price elasticity of the launch market with respect to the cost of launch. It will seek to answer to what extent the business models of newcomer rocket companies, such as SpaceX and new smallsat launchers, affects the size of the market for satellite applications. Particular note will be paid to alternatives to pure cost-per-kilogram impacts of new technology - for example, on the responsiveness of launch, and whether that can be provided by 'last mile', Momentus style delivery services in addition to the smallsat offering.

Hybrids:

This presentation will analyze the state of research on the behavior of Nitrous Oxide and other self-pressurizing oxidizers dynamically in tanks. It will discuss various models and in what scenarios they have been found to be more useful, as well as how this behavior, and the uncertainty in modeling it, affects component design and higher-level architecture. If possible, a variety of models will be tested against test data to illustrate.

Component Design:

This segment will review injector design and operation, including mixing and instability. A particular focus will be on how injector design interacts with throttling, with examples of especially deeply throttling architectures and how that affected the injector design. Design will also pay attention to how recent developments, including additive manufacturing, have opened up new design possibilities.