

Department of Aeronautics and Astronautics
School of Engineering
Massachusetts Institute of Technology

Graduate Program (S.M., Ph.D., Sc.D.)

Field: Space Propulsion

Date: October 15, 2013

1. Introduction and Purpose

The graduate program in the Department of Aeronautics and Astronautics at MIT provides educational opportunities in a wide variety of aerospace-related topics through academic subjects and research. The purpose of this document is to provide incoming masters and doctoral level students guidance in planning the subjects they will take during their graduate program. The suggestions outlined here are to be understood as guidance and not as a mandatory, rigid framework. The final decision as to which subjects are taken and in what sequence is to be decided between each student and their academic advisor and/or doctoral committee. In addition to these recommendations, the official S.M. and doctoral degree completion requirements must be taken into account during the design of a graduate program¹.

2. Motivation for studying Space Propulsion

Space Propulsion comprises the propulsion technology required to reach space, as well as that which can be used to maneuver in space. The first category (space access) remains confined to chemical rocketry, although some attempts continue to be made at electromagnetic or other alternative means of high-g propulsion. The in-space category, by contrast, has evolved towards the use of more mass-effective types of thruster, such as Electric Propulsion rockets, solar sails or electrodynamic tethers. The key difference in this case is the possibility of accumulating momentum for a long time, at the very low rate allowed by the limited supply of power available in space. Electric Propulsion (EP) has had a long laboratory maturation period, going back to the early 1960's, and has now reached the practical application stage, to the point that essentially all new satellites, commercial as well as scientific or military, now feature some form of EP as their nominal propulsion system. An intermediate category, Nuclear Thermal propulsion, exists in principle, although environmental, economical and sometimes political obstacles have prevented its application so far.

Chemical launch engines develop thrust levels that are many orders of magnitude larger than their in-space counterparts, and therefore any improvement to their performance would appear to offer correspondingly larger returns in terms of payload capability. On the other hand, for missions that require substantial cumulative velocity

¹ Refer to the S.M., Ph.D. and Sc.D. degree requirements in Aeronautics and Astronautics section of the MIT Bulletin, or to <http://aeroastro.mit.edu/graduate-program>

increments after reaching orbit, any improvement on the performance of the in-space propulsion system will reduce the payload for the launcher, thus allowing a proportional reduction of the launcher mass and cost. Chemical rockets have nearly reached their technological maturity, with improvements mainly being sought in the areas of reliability, cost, diagnostics or controllability. Some exceptions are the potential for active control of combustion instabilities, or the possible miniaturization of these rockets. In contrast, Electric Propulsion and its extensions are still far from mature, and offer many opportunities for both, incremental and possibly even revolutionary developments. Aside from immediate utilitarian considerations, students that specialize in this field have an opportunity to learn and use physics concepts that go beyond the usual Aero/Astro range, including plasma physics, micro- and nano-technology, high temperature fluid physics, etc, and can later access areas of technology that are also broader than usual.

Selected images from MIT space propulsion research are shown in Figure 1:

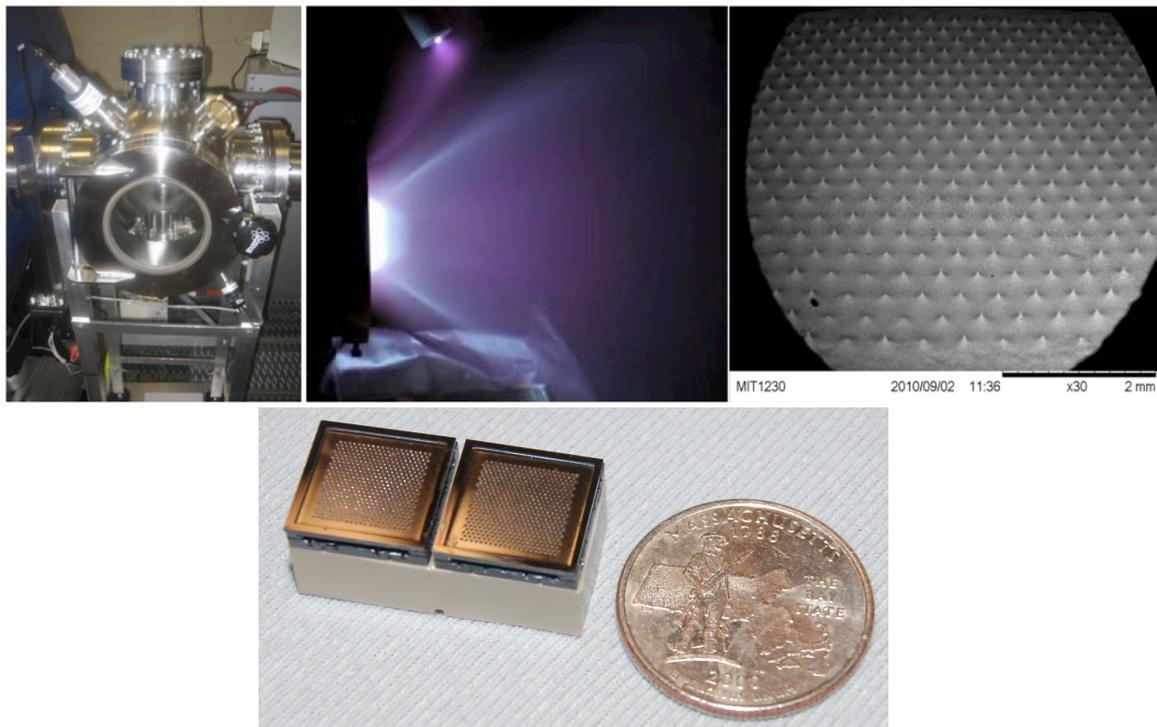


Figure 1. Left: A vacuum tank for testing micro-propulsion devices. Center: Plasma plume from the Divergent Cusped Field thruster. Right: Microfabricated array of electro-spray emitters. Bottom: MEMS Electro-spray thruster for small satellites

3. What is Space Propulsion Engineering?

Propulsion in general is a discipline that requires both, mastery of fundamentals and integration skills. A Space Propulsion specialist should be conversant with the requirements imposed by the overall mission goals (orbit dynamics, mass and power limitations, relative cost of time, etc), those imposed by the spacecraft itself (thermal

isolation between thrusters and bus, plume impingement effects and limitations, like voltage limitations and EM noise bounds), and methods for rationally selecting overall parameters (specific impulse, thrust and power level, etc) for optimal mission performance. But in addition, the specialist should also be familiar with the basic physics of the devices, which can be fairly sophisticated and unfamiliar to non-scientists. This is true even for engineers whose job will be to integrate propulsion systems into spacecraft, and it becomes essential for those whose job will be to develop and refine those thrusters. As an example of the former category, consider the task of integrating a high-power Hall thruster into a large and expensive spacecraft (civilian or military) that needs to have an orbital life of ten years or more. The Space Propulsion engineer will be responsible to ensure that stray ions from the high energy plasma beam issuing from the thruster will not erode the solar array coatings or damage the interconnects; this most likely will involve him or her in the running of critical tests and in tough technical arguments with the thruster manufacturer, and a sound command of the basic facts about the plasma, the materials and the engine physics will be necessary to arrive at satisfactory compromises. The case of an engine developer is more obvious: the very richness of the physics of Electric Propulsion guarantees that new thruster concepts, or modifications of existing ones will continue to appear as new and more demanding applications arise. Two recent examples, in fact driven by the physics, are the discovery of effective gas ionization over the magnetic pole separatrix in divergent cusped-field thrusters and the extraction of purely ionic beams in capillarity-fed electrospray thrusters: a way appears to be open to a new class of high performance engines, and only engineers with a sound training in the basics will be in a position to participate in their development.

4. Educational Goals in Space Propulsion

The educational goal of the MIT graduate program in Space Propulsion Engineering is to provide students with a foundational understanding and a working knowledge of the many technical issues surrounding the design, operation and integration of the propulsion systems used in space. This includes both, chemical and non-chemical types of propulsion systems, although the latter category is emphasized for its closer ties to research conducted at MIT.

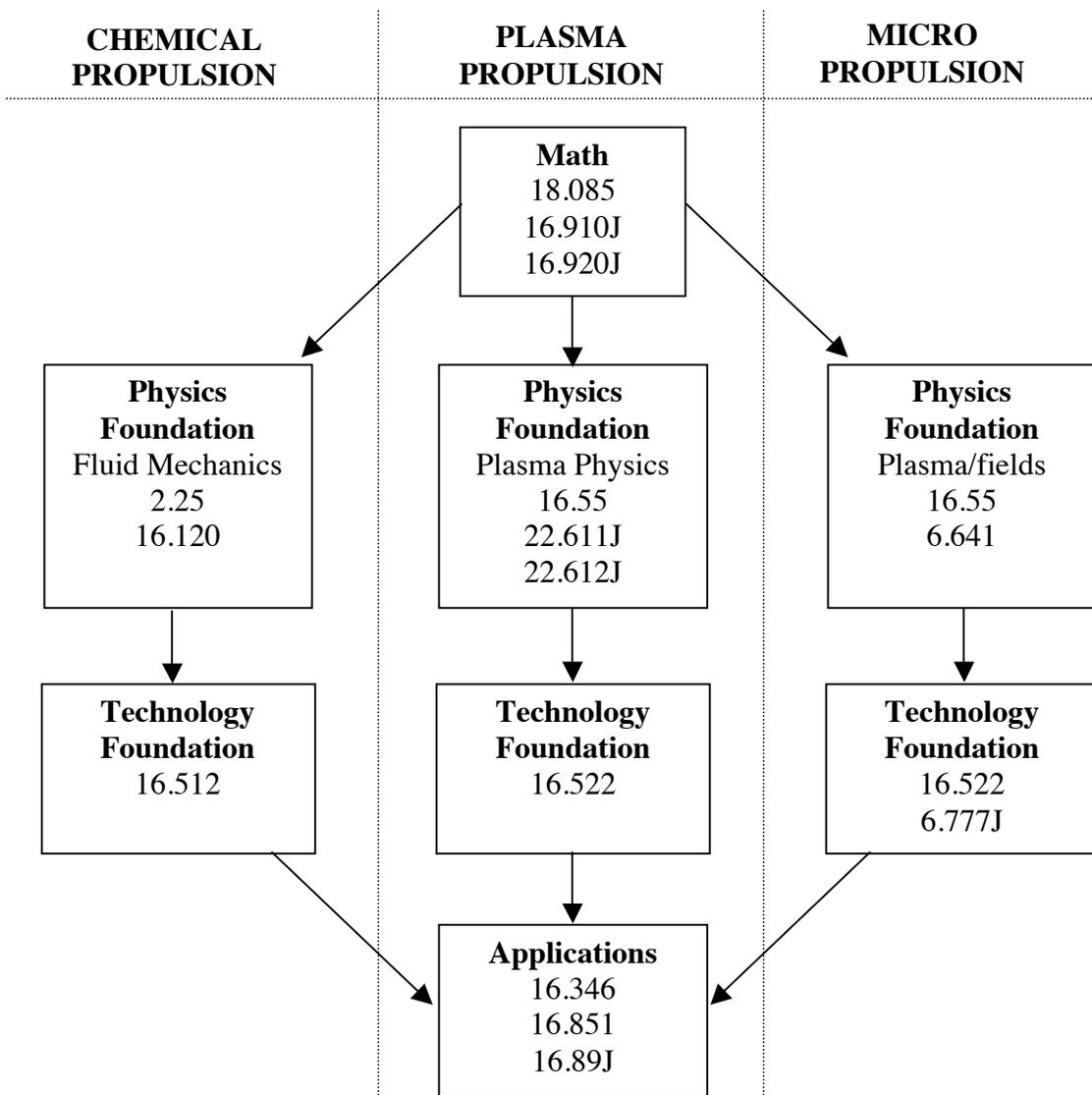
Successful graduates of the program will have:

- Acquired an understanding of propulsion system requirements and constraints, as dictated by the overall space mission goals.
- Gained a fundamental familiarity with the physical principles that underlie the production and control of the high-energy gas or plasma jets used in space propulsion.
- Generated research contributions to the current space propulsion engineering body of knowledge.

5. Educational Plan in Space Propulsion

The educational goals outlined above lead to a *Space Propulsion* program of study with emphasis in Chemical, Plasma or Micro- Propulsion (see Figure 2). This document outlines a program structure that will accommodate masters and doctoral candidates alike. It is important to mention that the program of study shown below represents a recommendation and not a list of requirements. Students are encouraged to base their final decisions on specific discussions with his or her advisor.

Figure 2. Space Propulsion Recommended Track



All students have to meet the departmental Mathematics Requirement (see separate document available from the graduate student office) with one graduate level mathematics course for the S.M. and two for the Ph.D. The department keeps a list of mathematics courses that are acceptable for fulfillment of this requirement. Suggested courses include Mathematical Methods for Engineers (18.085), a review of advanced undergraduate level mathematics, and Introduction to Numerical Simulation (16.910J) and Numerical Methods for Partial Differential Equations (16.920J), which have proven to be very useful to develop computational tools relevant to a number of physical phenomena studied in Space Propulsion.

The **Physics** foundation courses depend on the option chosen by the student. An emphasis on continuum fluid dynamics is suggested for students attracted by the field of chemical propulsion: Advanced Fluid Mechanics (2.25) and Compressible Flow (16.120). A solid background in Plasma Physics is recommended for the student interested in electric propulsion: Ionized Gases (16.55), Introduction to Plasma Physics I (16.611J) and II (16.612J). Finally, those wishing to study novel thruster regimes should receive additional instruction in the interaction of fields with matter: Electromagnetic Fields, Forces and Motion (6.641) or similar subjects.

The **Technology** foundation provides the student with the knowledge required to understand in depth the different types of propulsion systems. It consists of Rocket Propulsion (16.512), which studies in detail the components of chemical propulsion engines and their interactions, and Space Propulsion (16.522), a comprehensive review of thruster technologies applied to move spacecraft once they leave the Earth's atmosphere. Micropropulsion systems have benefited considerably on the development of Micro-Electro-Mechanical Systems (MEMS), this is why Design and Fabrication of MEMS (6.777J) or similar subjects become a crucial element of the micropropulsion option.

Propulsion sub-systems have an important influence on the design and operation of space missions. **Application** subjects such as Satellite Engineering (16.851) and Space Systems Engineering (16.89J) allow the student to understand system-wide interactions and design accordingly. Astrodynamics (16.346) provides the student with tools to calculate orbital elements and velocity changes for a particular mission or maneuver.

The S.M. degree subject requirement is 66 units, or a minimum of 6 courses. 42 of those units must be H-level and at least 21 should be from those offered by the Department of Aeronautics and Astronautics. A typical S.M. program in Space Propulsion would be comprised of a selection of subjects from the program of study shown in Figure 2. The following are three examples of S.M. programs based on these guidelines:

Example 1 <i>Study on Rocket Launchers</i>	Example 2 <i>Hall Thruster Modeling</i>	Example 3 <i>Electrospray Thruster Design</i>
16.910J	8.624	2.371
16.540	16.910J	16.920J
2.25	16.920J	16.55
16.512	16.55	6.641
16.346	22.612	16.522
16.89J	16.522	6.777J
16.891J	16.89J	16.851

Candidates for the Ph.D. degree are encouraged to register for most of the subjects described in the track. In addition, they are expected to complement their course plan with subjects recommended by their doctoral committee and with subjects that satisfy their minor requirement.

6. Courses related to Space Propulsion

2.28	Fundamentals and Applications of Combustion
2.37	Fundamentals of Nanoengineeri
2.62J	Fundamentals of Advanced Energy Conversion
2.625	Electrochem. Systems: Fundamentals, Materials and Applications
3.53	Electrochemical Processing of Materials
6.642	Continuum Electromechanics
6.781J	Nanostructure Fabrication
8.333	Statistical Mechanics I
8.624	Plasma Waves
16.540	Internal Flows in Turbomachines
16.891J/ESD.129J	Space Policy Seminar
22.616	Plasma Transport Theory
22.67	Principles of Plasma Diagnostics

7. Faculty and Staff with Interests in Space Propulsion

Hastings, Daniel (hastings@mit.edu)

Lozano, Paulo (plozano@mit.edu)

Martinez-Sanchez, Manuel (mmart@mit.edu)

Miller, David (millerd@mit.edu)

Please consult MIT Aero & Astro web-page for detailed faculty and staff interests:
<http://aerastro.mit.edu/faculty-research>