



AIAA 94-3112
**A Course in Advanced Space
Propulsion at The University of
Michigan**

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**30th AIAA/ASME/SAE/ASEE Joint
Propulsion Conference**
June 27-29, 1994 / Indianapolis, IN

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In response to the Space Exploration Initiative announced by President Bush a few years ago, a course on advanced (non-chemical) space propulsion at the senior, first-year graduate level was introduced and taught by the author. It was and is still open to students from the various engineering disciplines with no prerequisites other than the normal physics (including modern physics) and mathematics they are exposed to in their early undergraduate training. The course covers the various energy sources suitable for propulsion which in terms of specific energy (energy per unit mass) start with fission, and is followed by fusion and antimatter annihilation. Because of its high specific impulse relative to chemical propulsion, electric propulsion with its three main approaches, namely, electrothermal, electrostatic, and electromagnetic is included with special emphasis in each case on the accelerating mechanism and the energy needed to drive the system.

The disparity in the students' background, initially thought to be a major impediment to an effective course on the subject, did not actually materialize. In fact, the uniformity in the physics background of the students due to the

uniformity in training in their first two years, was actually desirable since that allowed the instructor to teach relevant physics topics from the standpoint of propulsion. A good example in this regard is the subject of special relativity which was introduced in the usual manner, but whose application was directed at the particles that result from proton-antiproton reactions, e.g., pions and their role in heating a propellant or in providing the propulsion themselves. The same approach was adopted in presenting the topics on fission or fusion since (with the exception of nuclear engineering students) most students have had little or no exposure to these topics. In short, by presenting the fundamentals and orienting the applications in the direction of propulsion very little disadvantage was felt by most students including those with what might appear to be a serious deficiency in their preparation. As a testimony to the success of this approach, the performance of the students on their homework problems was uniformly good with no major gaps that can be traced to inadequate background. One of the requirements for successful completion of the course is a term paper on an advanced propulsion concept and/or

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a related topic of the student's choosing. Here, again, no serious problems arose even though the students tended to pick topics that are the closest to their undergraduate specialty (major discipline). In what follows we will present the course content and some pedagogical comments on the topics covered.

Major Topics

The course content is summarized in Table 1. Eleven major topics are listed, and in a 15 week semester the coverage of some of these subjects had to be modest due to lack of time. Because of such constraint, one of the applications of nuclear energy, *i.e.*, propulsion, was emphasized relative to its power-generating

capability. Moreover, topics associated with power production such as energy conversion had to be addressed somewhat lightly. In addressing the three major components of the course, *i.e.*, fission, fusion and antimatter, considerable effort was expended in familiarizing the students with the basic concepts and the underlying nuclear reactions. In the case of fission-based propulsion the focus was placed on the solid-core nuclear thermal propulsion whose origin is traced to the NERVA rockets of 1960's, and on the gas core nuclear rocket which was introduced as a second generation nuclear thermal propulsion concept because of its considerably better propulsion capabilities. In each case the basic designs were examined, and the potential physics and

Table 1

Nuclear Energy for Space Power and Propulsion

1. Review of Energy Sources suitable for Space Application
2. The rocket equation, Specific Impulse and Thrust
3. Electric Propulsion — General Characteristics in terms of Specific Impulse and Jet Power
4. Electrothermal Acceleration, and Thermodynamics of High Temperature Gases
5. Electrostatic Acceleration and Ion Thrusters
6. Electromagnetic Acceleration, and the Magnetohydrodynamic Equations for EM Acceleration
7. Energy Conversion Schemes, both Static and Dynamic
8. Antimatter Based Propulsion, Elementary Particle Physics and Interaction of Charged Particles with Matter
9. Fusion Energy and Fusion-driven Propulsion
10. Applications of Fusion Energy to Space Power and Propulsion
11. The Gas Core Nuclear Rocket — Physics and Engineering Considerations

engineering problems that face the development of these concepts were discussed. For fusion propulsion, the two major approaches to terrestrial power reactors, namely, magnetic and inertial confinement, were examined highlighting the advantages and disadvantages of each in space propulsion. The use of antimatter annihilation reactions for propulsion is viewed in its role as a source of energy with which to heat a propellant, or in its capacity to

produce extremely energetic particles that can be exhausted through a nozzle to generate the desired thrust. With the latter scenario the use of special relativity becomes important in estimating the lifetime of these particles in the laboratory system, the distance they travel before they decay, and the use of magnetic fields to spatially confine and guide them. The role of the magnetic field in guiding these particles is addressed by means of lectures on magnetic

Table 2

Subjects of Homework Problems

1. Energy generation from various sources including specific energy (energy per unit mass), and converted mass fraction
2. Application of the rocket equation to the calculation of travel times and travel distances using a certain trajectory profile
3. Calculation of optimum specific impulse for a rocket when useful loads and power-producing systems are included
4. Calculation of propulsive parameters for an electrostatic ion thruster
5. Calculation of initial mass, propellant mass, travel times, *etc.*, for missions from earth to several planets using a propulsion system with given thrust and I_{sp}
6. Calculation of travel distances for energetic small particles using relativistic formulas and application of results to reaction products of proton-antiproton reactions
7. Evaluation of gas and/or solid heating by beams of charged particles, such as pions, traveling in hydrogen or deuterium targets
8. Calculation of magnetic fields needed to confine plasmas in magnetic mirror geometries, and calculation of the propulsion parameters for such systems
9. Systems analysis of inertial fusion rockets taking into account the efficiencies and *properties of various components*
10. Calculation of radiated power from a gas core nuclear rocket, and estimation of the neutron population in the system at different time intervals

nozzles in which the basic principles, along with the propulsive properties are presented using the magnetohydrodynamic equations. Development of a Bernoulli equation that is applicable to such nozzles is also presented and applied to some magnetic fusion configurations (*e.g.*, mirror machines) that lend themselves to such description. Because of the multiplicity of topics covered in this course, it was somewhat difficult to generate a set of homework problems that dealt with the subject matter on the one hand, and yet be sufficiently

basic to be meaningful, and attackable by the average student on the other. A total 10 sets, assigned over a period of 10 weeks, were used and covered the topics shown in Table 2.

As a measure of how effective and meaningful was the course to the students who took it surveys taken at the end of each semester reveal that the students valued the course very highly and would recommend it to their colleagues. On a scale of 1-5, with 5 being the highest, the students average rating of the course was 4.8.