A Course in

FUSION REACTOR TECHNOLOGY

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AS A CONSEQUENCE of growing interests of members of the Chemical Engineering Department at Princeton in research problems related to the development of thermonuclear fusion reactors, a program in fusion reactor technology was established in 1972 in the School of Engineering and Applied Science. This program provides a coordination of study and research at all degree levels for students interested in the engineering and technological aspects of controlled thermonuclear research. Readers interested in why a program in fusion reactor technology should be born in a ChE department are referred to the lively article by Axtmann [1] describing the contributions of chemical engineers to nuclear engineering.

The idea of controlling the fusion reactions of the hydrogen bomb for the generation of electric power originated in the then classified work of Project Matterhorn at Princeton and resulted in the first conceptual design of a fusion power reactor, the so-called Model D Stellarator report of Spitzer et al. [2]. Given the level of knowledge of the time, that report was singularly prescient in identifying the major scientific and technological problems that would have to be solved to achieve a practicable power generator. The problems of plasma physics were clearly of paramount importance, and as a consequence, a major theoretical and experimental program in plasma physics has developed at the Princeton Plasma Laboratory, the largest American enterprise devoted to controlled thermonuclear research and the only large one on a university campus.

Members of the ChE faculty have long been associated with the Plasma Physics Laboratory (two for more than twenty years) and involved in researches on various technological problems related to fusion power development. However, there had been little incentive to formalize a program in fusion reactor technology until recently when it became clear that the plasma physics problems were likely to be solvable and that the world energy situation would make fusion an increasingly attractive alternative source of energy.

COLLABORATION WITH PLASMA PHYSICS

THE PROGRAM IN fusion reactor technology was established in collaboration with the Plasma Physics Laboratory. There are six regularly enrolled graduate students in it plus about an equal number of undergraduates. Two full-time faculty and two part-time faculty are active in the program, and two other faculty members have related research interest. In addition there are, from time to time, visiting scholars from abroad.

Three courses involving fusion reactor technology are offered each year at Princeton. All three are taught in the Department of Chemical Engineering. Two are senior level undergraduate

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courses, Ch.E. 417 and 418, Nuclear Engineering I and II, and the third is Ch.E. 550, Fusion Technology, the graduate course described here. The first of the undergraduate courses is concerned primarily with fission processes, and fusion topics are introduced only briefly. The second undergraduate course, however, deals solely with fusion problems, emphasizing plasma behavior, the engineering aspects of plasma research, magnet design, and similar subjects. It provides a background useful for the graduate course.

Both undergraduate courses may be elected by graduate students and by properly qualified juniors and seniors. These courses are populated by students from a variety of engineering and science disciplines.

The graduate course was designed primarily for first-year graduate students in the fusion reactor technology program but a number of other students elect it as well. A principal objective is to provide an up-to-date perspective on the major problems and current researches in the technological aspects of fusion power development. The catalog description is:

Ch. E. 550. Fusion Reactor Technology

A study of contemporary problems in the development of nuclear fusion reactor systems. Plasma problems, fuel cycles, materials, blanket problems, energy extraction and power cycles, non-power uses of energy output, reactor control, environmental problems. Prerequisite: ChE 418 or equivalent.

Three faculty members share equally in the formal instruction in the course. They are Robert C. Axtmann, Professor of ChE for Environmental Studies, Ernest F. Johnson, Professor of ChE and Robert G. Mills, Head of the Fussion Reactor Design Division of the Plasma Physics Laboratory and Lecturer in ChE with rank of Professor. Approximately three-quarters of the class time is used for their lectures. The remaining quarter comprises seminars by students in the course and by other faculty members on selected topics in the field. Because of the disparateness of many of the topics the lecturers frequently alternate, and the seminars are scattered throughout the term albeit somewhat more heavily concentrated toward the end of the term.

There is no single textbook suited to this new field. Because of our historical and continuing link to the Plasma Physics Laboratory the principal focus of the treatment is on magnetically confined plasma machines rather than laser driven devices, and we tend to use as a major reference the conceptual design report edited by Mills [3] and published by the Plasma Physics Laboratory. This nearly 600-page report is the most detailed design study for a fusion power reactor currently available. This volume, with its numerous references, constitutes a comprehensive introduction to the field. The design is based on a minimal employment of new technology. In particular, materials of construction involve only those for which there is a proved fabrication capability. Even so, there are many uncertainties in the design since there are large areas of ignorance. These uncertainties are discussed at some length in the report, and hence they provide a good springboard for examining the major problems in fusion power development.

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Four copies of the Mills design report together with one each of the reference books listed below are placed on reserve in the Engineering Library for use by students during the course.

RESERVE LIST

1. "A Short Course in Fusion Power," NP-20040, USAEC, NTIS, 1972.
2. Chen, Francis F., "Introduction to Plasma Physics," Plenum Press, New York, 1974.
3. Glasstone, S., and R. H. Lovberg, "Controlled Thermonuclear Reactions," D. Van Nostrand Co., Princteon, New Jersey, 1960.
4. Gruen, D. M., editor, "The Chemistry of Fusion Technology," Plenum Press, New York, 1972.
5. Kammash, T., "Fusion Reactor Physics Principles and Technology," Ann Arbor Science Publications, Inc., Ann Arbor, Michigan, 1975.
6. Mills, R. G., editor, "A Fusion Power Plant," MATT 1050 Princeton Plasma Physics Laboratory, Princeton, New Jersey, 1974 (available through NTIS, U. S. Department of Commerce, Springfield, Virginia 22151).
7. Rose, D. J., and M. L. Clark, "Plasmas and Controlled Fusion," MIT Press, Cambridge, Massachusetts, 1961.

In addition to the reserved books there are strong collections of publications on fusion technology maintained by the Engineering Library and also by a satellite library at the Plasma Physics Laboratory on the Forrestal Campus. Many of these publications are in the form of proceedings of international symposia and workshops on specialized aspects of fusion technology sponsored by various agencies like Energy Research and Development Administration (ERDA) and technical societies like the American Nuclear Society and the Institute of Electrical and Electronics Engineers (IEEE).

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Because of the rapid growth of knowledge in many aspects of fusion technology and shifting emphases as new constraints arise and old ones change, the content of the course will vary from year to year. Last fall the formal coverage included a brief overview of the world energy problem to show what contributions might be expected of fusion power, a detailed review of the Princeton Reference Design to identify the major problems and some possible solutions, a treatment of the problems of plasma physics as a basis for setting the scale of realistic machines and fixing many of their properties, and an examination of the environmental problems arising from power plants generally and from fusion power plants in particular.

Although some problems had to be treated cursorily, either for lack of time or because current understanding is uncertain, every major problem was addressed in the formal part of the course. Some like the use of molten salts as tritium breeding media the permeation of hydrogen isotopes in metals were addressed in greater detail because of the special interests of particular faculty members.

During the term eight seminars were conducted in the course on the following subjects:

1. **Low Concentration Permeation**
2. **Ion Bombardment of Metals**
3. **Fission-Fusion Hybrids**
4. **Parametric Systems Analysis**
5. **Laser Fusion**
6. **Alternate Fuel Cycles**
7. **Non-Power Uses of Fusion**
8. **Fuel Injection**

Concurrently with the graduate course in fusion reactor technology a series of ten seminars on vacuum technology and engineering was offered by a physicist from the Plasma Physics Laboratory as part of the program in fusion reactor technology. A similar seminar series on neutronics was offered during the preceding term. As a consequence neither of these topics was discussed in any detail in the graduate course.

Although we have offered the course only once, our assessment, arrived at in consultation with our students, is that we have fairly met our objectives. We anticipate that we will follow essentially the same format when we offer the course again this fall. In contrast with the first offering we shall probably include some homework problems and examinations to provide a better feedback on our teaching. □

REFERENCES

1. Axtmann, R. C., Nuclear Technology *27* 78-83 (1975).
2. Spitzer, L., Jr., D. J. Grove, W. E. Johnson, L. Tonks, and W. F. Westendorp, Problems of the Stellarator as a Useful Power Source, NYO-6047, U. S. Atomic Energy Commission (1954).
3. Mills, R. G., editor, "A Fusion Power Plant," MATT 1050, Princeton Plasma Physics Laboratory, Princeton, N. J. 1974 (available through NTIS, U. S. Department of Commerce, Springfield, Va. 22151).

DE KEE: Food Engineering

Continued from page 167.

19. F. C. Webb, *Biochemical Engineering*, Van Nostrand, New York, (1964).
20. *Chemical Engineering Progress Symposium Series*, 68 volume 64, Bioengineering-Food, (1968).
21. *Chemical Engineering Progress Symposium Series*, 69, volume 62, Bioengineering and Food Processing, (1966).
22. D. De Kee, M.A. SC. Thesis, University of Ottawa, (1974).
23. *Chemical Engineering*, Jan. 4, "Continuous Beer Making Makes Commercial Debut," (1965).
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25. T. Kono and T. Asai, *Biotechnol. Bioeng.*, 11, 293, 1969.
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