PREFACE

Space vehicles, launched by rocket and injected into earth satellite orbits or interplanetary trajectories, require lightweight, on-board, self-contained power generating equipment to energize radio transmitters and receivers, scientific instruments, attitude and velocity control devices, and other apparatus. Such electric power generators represent a novel field of development that has been stimulated largely by the severe demands of satellites and space probes. Whereas submarines aircraft, and ballistic missiles - all highly advanced vehicles - have also required self-contained power sources, the space vehicle has imposed much stronger and sometimes opposing requirements, namely, light weight, long life, and high reliability.

Development of space vehicles is at present being hampered by the unavailability of such long-lived, reliable electrical power sources. Each of the many different kinds of space power systems now under consideration presents its own peculiar problems and limitations.

Solar cell systems, for example, which make use of the only source of energy available in space itself are expensive and elaborate because of the disappointingly low density of solar energy, thus necessitating the use of very large collectors. Also, the energy must be stored in electrochemical batteries for use when the vehicle is in the shadow of the earth or other planets, which further adds to the cost and complexity. Moreover, solar cells are affected deleteriously by corpuscular radiation in space.

Chemical fuel, carried on the vehicle, can be used to provide a compact system for use in relatively short-term missions (1-20 days), but poses a weight problem in long-term missions.

Nuclear reactor systems result in radiation problems especially when manned space flight is considered. The use of turbo-machinery involves moving parts which must operate flawlessly for long periods in the presence of unusual gases such as light metal vapors, and condensation of such vapors requires the use of large radiators susceptible to micrometeorite puncture.

High temperatures are required for thermionic energy conversion in order to develop high efficiency and small radiators, and efficiencies predicted at present are inadequate. Thermoelectric solid-state elements might be used at lower temperatures for smaller powerplants, but for large amounts of power, thermoelectric materials must be developed which operate at high temperatures so as to keep the radiator small. Such materials have been discovered but are not yet developed for use.

Solar mirrors appear attractive because there is no radiation problem, as there is with nuclear reactors, and because they are lighter than solar cells. However, there are serious problems in obtaining high accuracies in mirror surfaces and orientation after they are unfolded in space.

These and many other problems involved in the development of space power systems were discussed at the Space Power Systems Conference held in Santa Monica, California, September 27-30, 1960, under the sponsorship of the American Rocket Society's Power Systems Committee, in co-operation with the American Institute of Electrical Engineers, the Institute of Radio Engineers, and the Interservice Group for Flight Vehicle Power. The meeting also enjoyed the support of the Department of Defense, the military services, the Atomic Energy Commission, the National Aeronautics and Space Administration, the Institute for Defense Analyses, and the Advanced Research Projects Agency.

Because of the extensive coverage of the field provided at Santa Monica, it was decided to publish two volumes, rather than one, based on papers presented at the meeting. These two volumes comprise numbers 3 and 4 in the ARS Series on Progress in Astronautics and Rocketry. Volume 3 is particularly concerned with the scientific and engineering principles involved in the conversion of various types of energy into electrical energy, while Volume 4 is devoted to systems for the production of electric power which are based on these principles. The two volumes are independent but, taken together, constitute an extensive analysis of the broad field of space power systems.

Except for the use of primary batteries alone in short-life space flight, the solar-cell, nickel-cadmium battery system is the only power source used thus far in American space vehicles and, to our best knowledge, in those developed by other countries. Its use can be expected to continue for the next few years for power requirements up to 1 kw. Use of a radioactive thermoelectric power source such as SNAP III may also be anticipated, although it can only be competitive with solar cell systems on the basis of reliability and will not provide power above 10-20 watts.

For certain missions, chemical systems may be desirable. Use of a hydrogen-oxygen system, coupled with a turbo-electric generator, appears feasible for short-term flights around the earth or around the moon and back to earth, lasting from 5 to 10 days. The same system, coupled with a fuel cell, might also be used to provide power for missions lasting from 20 to 30 days.

Whatever system is used for space missions, the determining factor in the eventual choice is likely to be its reliability, rather than its efficiency. While weight per unit power is important in view of present space vehicle weight limitations, undue emphasis is sometimes placed on the efficiency of energy conversion systems. High reliability is still of prime importance, and must be achieved even at the expense of efficiency.

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Volume 4, devoted to "Space Power Systems," consists of four sections. The first three sections involve systems based on the three primary sources of energy of practical value, solar, nuclear, and chemical, while the fourth section is devoted to the requirements for space power.

The section on solar systems starts with a paper by Snyder and Karcher on general aspects of solar cell power systems based on the work performed for U.S.A. space vehicles that were or are to be placed in orbit. Of particular interest is a graph showing the variation of characteristic parameters of the solar cell battery storage system as a function of flight altitude. More specific details are given in the succeeding four papers on the solar cell power plant for the space vehicles ADVENT, RANGER, TIROS, and TRANSIT. Although several other kinds of power systems are discussed in this and other sections of Volume 4, none of them is ready for practical operation and none is yet competitive with the solar cell system.

In some cases, the development is embryonic and a clear evaluation cannot be made for some time, as in the case of solar mirror systems. In other cases, good performance appears feasible but much research, engineering, and testing will have to be accomplished, both on the ground and in flight, as is the case with the nuclear reactor, turbo-electric, or thermo-electric powerplants.

The sixth paper, by Evans et al., presents a rather detailed analysis of the physics and engineering of solar panel design. Of particular interest is the heat balance as affected by solar cell covers and coatings, as well as the protection by the quartz covers against radiation.

Papers by Silvern and McClelland present an analysis of mirror accuracy requirements and design parameters for a practical space mirror powerplant system. The paper by McClelland shows that high temperatures of approximately 1000 to 1300°C will require accuracies of the mirror surface and mirror orientation which will be difficult to obtain with light-weight systems.

The papers by Purdy, Henderson and Dresser, and Rudy provide a fairly clear picture of the problems that will be encountered in the areas of solar mirror thermionics, solar mirror stirling engines, and solar mirror turbo-machinery systems, respectively. A solar mirror-thermoelectric system paper was not available at the conference and is not included; however, a very interesting development involving the flat plate thermoelectric generator is given by Campana and Roes.

In general, the papers involving solar mirrors show remarkable scientific and engineering advances over that which had been previously known and developed over the past ten or fifteen years, and this was accomplished in only the last two years. Reflected in these papers is the intense work by highly qualified scientists and engineers to achieve a light-weight, highly accurate solar mirror system which is reliable for operational times in space of one year or more. The flat plate thermoelectric generator has an advantage over solar cells in being relatively unaffected by Van Allen radiation. However, the efficiencies shown are quite small by comparison, and large surfaces will be required.

The section on nuclear systems includes a series of papers involving the various aspects of the Atomic Energy Commission SNAP (Systems for Nuclear Auxiliary Power) program. Many details are presented for the 3 kw, liquid metal, turbo-machinery SNAP II power systems covering subjects from the basic concept through vehicle integration and safety aspects. Developments in the SNAP X nuclear reactor thermoelectric program are presented also. Some prospective applications of the SNAP reactors are given by Wetch and Lundholm. Information on the 30 kw SNAP VIII reactor system was not included because work on it was initiated only recently.

Use of thermionic converters integral with the fuel element of a nuclear reactor and the associated system are discussed in two papers, one by Hirsch and Holland, and one by Perry, based on proposed systems which have not been constructed. Their estimates show that specific weights of 10 lb/kw or less are possible, depending on shielding requirements and operational loads above 100 kw. Because thermionic diodes operate at high temperatures, high radiator temperatures are a consequence, resulting in advantageously smaller surface areas for heat dissipation, it is claimed.

A paper by Johnson attempts to prove that liquid metal cooled, turbo-machinery systems will be lighter and more reliable than thermionic systems. Fuel elements in thermionic diode reactors must operate near 2000°C, an exceedingly difficult performance goal to attain when considering one or two years of lifetime. Five to ten years of extensive materials research may or may not lead to a satisfactory solution. There if definite disagreement between Johnson and proponents of the thermionic nuclear reactor on details of what is or is not possible in the development of that type of reactor. Research in this field has been only recently begun (with some of the results given in the second section of Volume 3), and many more results must be forthcoming before definite conclusions can be reached.

In the paper by Cochran and Buck, an analysis is made which shows the major advantages and disadvantages of having a non-boiling or boiling liquid metal cooled reactor system. Until better information is obtained on the heat transfer and fluid dynamics of boiling liquid metals, a more definitive conclusion cannot be reached, it is claimed.

The compact and apparently highly reliable radioisotope thermoelectric generator is discussed in three papers. Bloom and Weddell discuss a well conceived design of a small curium-242 powered device which can be used on Lunar impact missions. Greenfield shows that an optimization of the SNAP III radioisotope power device can increase the initial available power by as much as a factor of four over the original model, which developed an initial 5 watts in a ground environment (free convection heat dissipation). The analysis is simple and is substantiated by an experiment. The relative safety of using a radioisotope for space flight is discussed by Dick. One can conclude that there is sufficient engineering skill today to design a safe system.

Chemical systems have not excited much attention in the scientific world because they appeared to be "old hat." Nevertheless, the recent developments of missile and aircraft auxiliary power systems can provide the basis for compact piston or turbomachinery systems of the chemically fueled type for short-time missions in space. In the section on Chemical Systems, Zwick presents a general survey of accomplishments to date with certain comparisons of great value to the reader. The paper by Bell and Reid provides an excellent picture with good references of the methods of storing and expelling high energy cryogenic fuels. Such a system can provide from two to five times more energy per unit weight than the silver-zinc primary battery.

The section on space power requirements provides the seasoning for both Volumes 3 and 4. One asks the question: What space vehicles are to be launched in the next ten to fifteen years, and how much electrical power will be needed in each case? The paper by Finger and Schulman discusses NASA requirements on a fairly specific basis up to 1965 only. Some vehicles which will be launched at a later time are briefly mentioned with possible power requirements. The paper by Kelly provides a less specific set of requirements, but prognosticates far into the future with an indication of the size of powerplant and when its development must be started. It is argued that powerplants in the multikilowatt and megawatt range will take as much as ten to fifteen years to develop for satisfactory space operation. The 3 kw SNAP II reactor system was initiated five years ago and will need perhaps another five years of development before an operational flight unit is feasible. The growth rate of space vehicles may be seriously limited by the unavailability of satisfactory electric power supplies. Kelly's paper provides an interesting and useful estimation of the many requirements that are likely to become firm in the future.

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The Editor would be remiss in his duty if he did not gratefully acknowledge the invaluable aid provided in developing the technical program for the Santa Monica Conference by the various session chairmen. These chairmen, and the corresponding sessions for which they were responsible, are:

Thermoelectricity - Paul H. Egli,U. S. Naval Research Laboratory, Washington, D. C.

Thermionics - Wayne B. Nottingham, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Photovoltaic Cells - Paul Rappaport, Radio Corporation of America, Princeton, New Jersey.

Electrochemical Cells - Arthur F. Daniel, U. S. Army Signal Research & Development Laboratory, Fort Monmouth, New Jersey

Solar System - George Sherman, Wright Air Development Division, Wright-Patterson AFB, Ohio

Dynamic Engines and Plasma Generators - Gordon Banerian, Aerojet-General Nucleonics, San Ramon, California

Systems for Nuclear Auxiliary Power and Applications Safety and Advanced Systems - Guveren M. Anderson, Atomic Energy Commission, Washington, D. C.

Walter K. Deacon of Vickers Incorporated, Torrance, California, was General Chairman of the Conference, while the Editor served as Technical Program Chairman.

Much credit is due Abe M. Zarem of Electro-Optical Systems, Inc., Pasadena, California, 1960 Chairman of the American Rocket Society Power Systems Committee, who did a great deal to develop ARS interest in space power and was instrumental in initiating the Conference and making it a success.

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Nathan W. Snyder
Volume Editor