Solar Cell Array Design Handbook

The Principles and Technology of Photovoltaic Energy Conversion

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Preface

Solar cells and solar cell arrays—photovoltaic converters of solar energy into electric energy—are a reality. In a time period of two decades, solar cell arrays have grown in size from less than 1 watt to hundreds of kilowatts of electrical output in terrestrial applications and to over 10 kilowatts of output in space. New designs are on the drawing boards and in development laboratories all over the world for terrestrial and space arrays having hundreds and thousands of kilowatts of electric power output. Solar cell efficiency has increased from just a feeble response to sunlight to nearly 20%, surpassing the luminous efficiency of the incandescent light bulb on the way. Solar cell array costs are decreasing rapidly, making photovoltaic electric energy affordable and competitive today in remote areas.

In the same two-decade time span, the solar cell array design effort has matured from a spirited pioneering effort into a sophisticated, systematized, computer-aided process. While it has not been possible to adequately define or improve, or otherwise influence the creative design activity, all other aspects of the design process have been formalized and, for good reason, subjected to documentation, control, and verification.

As the 1970's draw to a close, we find ourselves engulfed by flurrying activities in photovoltaics. While we stand at the threshold of an unprecedented economical exploitation of this particular solar energy conversion technology, we should also realize that all the "easy" inventions have perhaps been made already. From here on, the going can be expected to get tougher. It is hoped that this book will be helpful to those who are going to keep on working for the benefit to all of use who consume energy.

Hans S. Rauschenbach

Purpose and Scope of this Handbook

This handbook intends to diseminate as much current and practical information relating to photovoltaic energy conversion technology for earth and space applications as practical. The emphasis is on the presentation of many different concepts and detailed techniques for several reasons:

- To introduce non-technical persons to the subject
- To aid students of the subject and younger workers in this field in mastering it
- To help specialists already working in the field to get their jobs done more effectively
- To inspire the creativity of advanced designers
- To document those concepts, data, and information that are of interest today but are not readily available in the open literature
- To define the entire field of solar cell array design and its multidisciplinary nature.

This handbook is written on several levels, ranging from the illustrative and introductory to the detailed technical. Most of the text should be understandable to advanced high school students and senior technicians. Few sections, if any, are expected to pose difficulties for college graduates or practicing engineers.

The mathematical treatment has been held simple. Differential and integral equations are used sparingly, but are included to permit computer programming. Most mathematical problems can be handled with today's scientific pocket calculators.

This handbook recounts some of the more important historical events that led to today's advanced solar cell array technology and includes sufficient references for locating more detailed accounts. Subjects that are treated elsewhere and readily available, such as general structural design, heat transfer and thermodynamics, civil engineering, and electrical wiring codes and practices, are not included here. Rather, only the special considerations for solar cell arrays are treated.

LEGAL NOTICE

This handbook attempts to document the knowledge, data, and information which may be of current significance to solar cell array design. However, it is emphasized that there exists a large number of patents which relate to all aspects of solar cell array design, fabrication, and testing, including solar cells, other materials, processes, components, arrangements, and designs. Some of these patents have been described herein, but many more have not been referred to. The description in this handbook of any component, process, apparatus, material,

design, composition, or any other feature of any article may fall within a claim of an existing patent. It is not the intent of any of the authors, editors, and publishers of and contributors to this handbook–nor is it the intent of any of the sponsoring or performing organizations involved in the preparation of this or the original handbook–to induce anyone to infringe upon any existing patent. It is the responsibility of the prospective user of any of the information, material, data, and descriptions herein to determine whether such usage constitutes infringement or noninfrigement of any patent or otherwise legally protected or proprietary right.

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SAFETY NOTICE

Solar cell assemblies, modules, panels, or arrays are sources of electric power and may, under certain circumstances, constitute a potential hazard. Even under conditions of low ambient lighting, a sufficient number of solar cells connected in series may produce voltages and currents that may cause electrocution. Appropriate safety procedures for handling and installing such assemblies must be used and followed (see also the entries under Safety in the Index).

A larger array, when exposed to bright sunlight and short-circuited with a conductor having inadequate cross-section, may start a fire.

Any solar cell assembly, even in low ambient light, when accidentally short-circuited, may cause a spark that is capable of igniting explosive atmospheres, such as may be found in solvent cleaning operations.

Acknowledgments

This handbook is a completely revised, updated, and expanded issue of an earlier, space technology oriented document published in October 1976 and now available as NASA CR-149365 [N77-14193 (Vol. 1) and N77-14194 (Vol. 2)]: *Solar Cell Array Design Handbook*, from the National Technical Information Service, Springfield, Virginia 22151.

The earlier handbood was prepared by the Power Sources Engineering Department of TRW Defense and Space Systems Group, Space Vehicles Division (author and editor, H. S. Rauschenbach), under Contract No. 953913 with the California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California. The active support in the creation of the original document of E. Cohn at NASA Headquarters, J. V. Goldsmith and R. Josephs at JPL, and the following at TRW is gratefully acknowledged and appreciated:

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Credit goes also to the literally thousands of workers who, over the years, have created the large body of photovoltaic knowledge and technology from which this author has drawn, and to the institutions of higher learning, private industry, and government which contributed to it in some indispensable way. Since a book of this nature cannot name them all, and naming of only a few would be highly inequitable, names of individuals and organizations have been deleted entirely, except where essential, from the text. Those included in the references were not selected according to the significance of their work, but rather to provide the researcher with leads for a greater in-depth pursuit of a particular topic.

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