Photovoltaic Array Reliability Optimization

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Key Words—**Photovoltaics, Solar cell, Circuit design, Fault tolerance.**

Reader Aids—
Purpose: Tutorial
Special math needed for explanations: None
Special math needed to use results: None
Results useful to: Photovoltaic module & system manufacturers and users

Abstract—**Several statistical reliability studies have been conducted in areas of photovoltaic component design covering cell failure, interconnect fatigue, glass breakage and electrical insulation breakdown. This paper integrates the results from these studies and draws general conclusions relative to optimal reliability features for modules. The analysis is based on designing for specified low levels of component failures and then controlling the degrading effects of the failures through the use of fault tolerant circuitry and module replacement. Means of selecting the cost-optimal level of component failures, circuit redundancy, and module replacement are described.**

INTRODUCTION

The reliability of photovoltaic solar arrays is probably second in importance only to cost in the list of factors influencing the market acceptance of this new technology. Because of their uniquely modular nature, photovoltaic arrays possess a higher than normal sensitivity to common-mode failures, but at the same time offer a wealth of redundancy options to increase reliability. Achieving the high reliability demanded by large-scale application requires that these unique reliability design attributes be well understood and used effectively.

As part of the Jet Propulsion Laboratory's Flat-plate Solar Array project a comprehensive array engineering activity has been addressed to understanding the reliability attributes of terrestrial flat-plate photovoltaic arrays and to deriving analysis and design tools useful for array optimization and cost reduction. This paper provides an overview of the array reliability problem and defines a rational approach to achieving high reliability at minimum cost.

At the root of the reliability problem is the need to electrically interconnect thousands of nearly identical solar cells in series and parallel to achieve the voltage and current levels of the intended application. For example, a typical 250 V residential array requires 500 to 600 series cells, and a typical 1500 V central station application will require 2000 to 3000. This large number of series elements makes an array extremely sensitive to cell failures unless a high level of circuit redundancy is used.

The reliability engineering problem is to achieve a high level of reliability at low cost by optimally trading off the available solution strategies. These include defining and achieving the appropriate piece part failure rates for the cells and interconnecting components, designing the appropriate levels of fault tolerance into the array circuit, and selecting the optimal maintenance/replacement strategy. In the remainder of this paper each of these solution strategies is explored and then combined to define least-cost solutions based on minimum life-cycle energy cost for the total system.

CONTROLLING PIECE PART FAILURES

One solution strategy centers on controlling component failure mechanisms and rates. These are most easily considered in two categories: those generally associated with failure at the solar cell level, and those associated with failure at the module level. Solar cell failures are primarily cell cracking, interconnect open circuits, and increased cell metallization contact resistance.

Cell Cracking

Of the cell failures currently seen in the field, cell cracking is by far the most prevalent and is occurring at a rate of about 1% per year. Although only 1% to 10% of these cracked cells have resulted in open-circuit cell failures, even this small failure rate can lead to substantial array power degradation. Reducing the power degradation by further reducing the cell failure rate is difficult because of the unavailability of predictive design techniques to determine when a design has achieved a desired failure level. Present rates have been quantified only after expensive auditing of actual field performance.

The three primary causes of cell cracking appear to be: differential expansion between the cell and its support, impact loading by hailstones, and reduced strength due to cell damage occurring during cell processing and module assembly. Although qualitative design techniques exist which address the first two causes [1, 2], cell strength data is limited to near average cells by the sample sizes available for testing [3]. This lack of strength and stress data on the one-out-of-thousand worst case cell which is responsible for field failures places a high reliance on test techniques such as those defined in [4] and on the use of fault tolerant circuitry such as multiple cell interconnects.

Cell Interconnects

Cell interconnects are both an important tool for reliability improvement and a source of failures. Given that a cell has cracked or otherwise degraded in a local

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area, the extent of module or array degradation can be substantially lessened by electrically attaching to the cell at more than one location. One means of assessing the degree of improvement possible is to analytically consider a large number of randomly oriented potential cracks and then to determine the fraction which would lead to open-circuiting or significant cell degradation (>10% area loss). Many of the latest module designs are taking advantage of multiple interconnect attachment points and are expected to have substantially lowered failure rates. With present cell failure rates at about 0.01% per year it is expected that the improved redundancy will lead to values approaching 0.001% per year.

The above optimistic projection assumes that the interconnects themselves don't fail, but of course they do. Interconnect open circuiting due to mechanical fatigue is an historical photovoltaic array failure mode and has even recently taken its toll on some modern installations. Like cell breakage it is primarily caused by thermal and humidity expansion differencies between the cell and its supporting substrate or superstrate. Also like cell breakage, interconnect fatigue is not easily predicted by available analytic models until the level of failure reaches major proportions. Mon, Moore & Ross [5], for example, have shown that the work of Manson [6] together with finite-element stress-analysis of the cell-interconnect provides excellent prediction of the number of cycles required to fail 50% of the interconnects. In addition, they have empirically characterized the probability of failure of a variety of photovoltaic interconnects versus number-of-cycles (figure 1) and developed a fatigue curve which treats probability-of-failure as a parameter (figure 2). As can be seen from figure 1, even identically loaded interconnects can be expected to fail in a statistically independent manner over a broad range of cycles, the weakest failing at 1% of the average life.

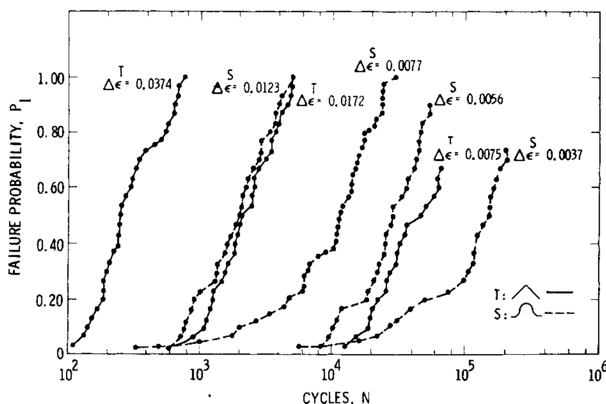

Fig. 1. Cyclic mechanical fatigue test data for two copper interconnect shapes (T, S) and peak-to-peak strains ($\Delta\varepsilon$).

As with cell cracking, the solution is to design for a manageable number of failures (maybe 10% during the array design life) and then to incorporate interconnect redundancy to control power losses associated with those that fail. For example, if 3 interconnects were used to connect each cell, 10% failed interconnects would lead to 0.1% cell failures at the array design life.

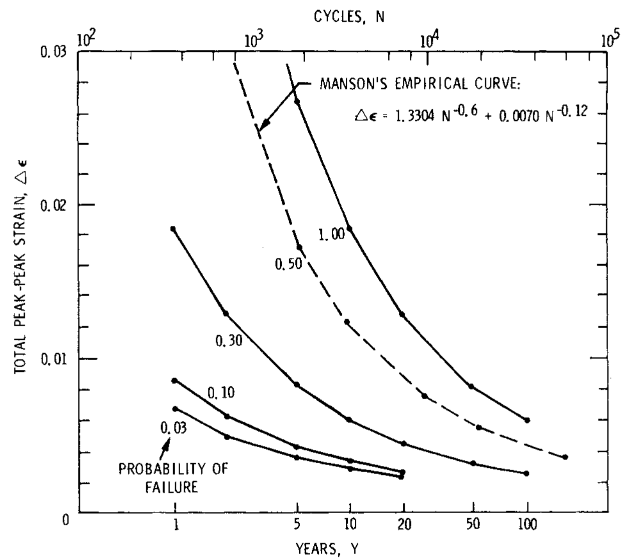

Fig. 2. Interconnect strain-cycle fatigue curves with failure probability as a parameter.

Module-Level Failures

In addition to failure modes which are best treated at the cell level, there are a number of failures which are more appropriately considered at the module level. These include glass breakage, electrical insulation breakdown, and various types of major encapsulant failure such as delamination. Like cell failures these failures are also flaw related and must be treated statistically when considering quantities of modules in a large array. Moore [7] and Mon [8] in work with me have developed empirical and analytic tools for designing for given statistical levels of glass breakage and electrical breakdown, respectively.

When designing for appropriate levels of module failures it is important to note that a module failure is likely to cause an electrical hazard or major power loss and will therefore require immediate maintenance or replacement. As a result module failure rates are traded off against life-cycle maintenance costs, as opposed to redundancy and life-cycle energy loss which are associated with cell failures.

FAULT TOLERANT CIRCUIT DESIGN

Given that the component failure rates have been reduced to manageable levels, it is necessary to introduce circuit redundancy features to control the effect of the remaining few failures on module yield and array power degradation.

Array Degradation

The first step toward circuit redundancy is generally associated with dividing the large matrix of cells in the

array into a number of parallel solar cell networks referred to as branch circuits. The branch circuits provide convenient points for monitoring array performance and provide an ability to isolate small areas of the total array for maintenance and repair. As shown in figure 3 each branch circuit can contain a single string of series solar cells or a number of parallel strings interconnected periodically by cross ties. The cross ties divide each branch circuit into a number of series blocks. One or more series blocks can also be bridged by a by-pass diode which is designed to carry the branch-circuit current in the event that local failures constrict the current flow to the point of voltage reversal and power dissipation.

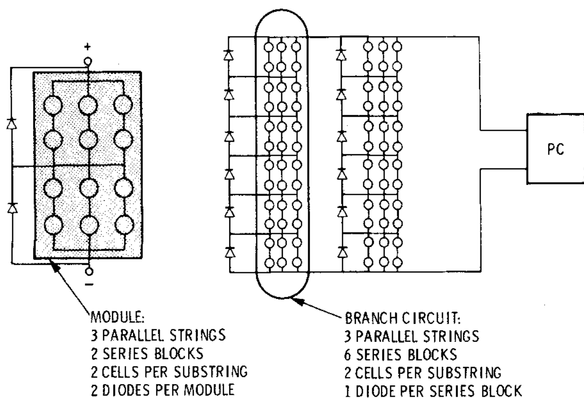

Fig. 3. Series-parallel nomenclature.

A key problem in using these circuit redundancy features has been in quantifying the influence of specific series/parallel and by-pass diode arrangements on array degradation. This problem has been recently solved by the development of an elaborate parametric analysis based on the statistical distribution of failed substrings due to random cell open-circuit failures [9, 10]. Given a specific branch circuit configuration the sub-string failure probability (F_{ss}) can be easily computed from the cell failure probability (F_c) and the number of cells per substring (n) using (1), as long as all failures are statistically independent.

$$F_{ss} = 1 - (1 - F_c)^n \quad (1)$$

Ref. [10] contains a large number of parametric plots, an example of which is shown in figure 4, which allows rapid computation of the effects of circuit redundancy on array power loss.

To assess the level of reliability improvement which can be achieved, it is instructive to consider the problem of calculating the anticipated power degradation after five years for a 1000 V large ground-mounted array with 0.01% cell failure per year. To achieve the 1000 V nominal operating voltage requires approximately 2400 series solar cells per branch circuit. Let us further assume that the array is composed of 1.2 × 1.2-m (4 × 4-ft) modules each containing 144 solar cells. If the modules contain a single

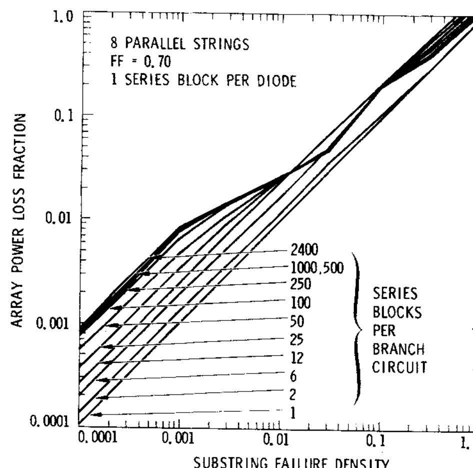

Fig. 4. Array power loss as a function of substring failure density, for 8-parallel-string branch circuits with one diode per series block.

series string of 144 cells and no by-pass diodes, each branch circuit could be made of 17 series modules giving a total of 2448 series cells.

Calculation of the anticipated array degradation after 5 years can be accomplished using figure 4 by noting that the configuration is identical to 8-parallel cells by one series block. However, (1) must first be used to compute substring failure probability at the end of five years. Thus:

$$F_{ss} = 1 - (1 - 0.0005)^{2448} = 70.6\%.$$

Using figure 4, or simply noting that the branch circuit and substring are the same, indicates that with only 0.01% cell failure per year, the array is over 70 percent degraded after five years.

By way of contrast consider instead that the 144-cell module is reconfigured to consist of 8 parallel cells by two series blocks with 9 cells per substring, and one by-pass diode per series block. A branch circuit is now composed of 2448/18 = 136 series modules and contains 272 series blocks. The substring failure probability is:

$$F_{ss} = 1 - (1 - 0.0005)^9 = 0.449\%.$$

Entering figure 4 with this substring failure density and interpolating for 272 series blocks indicates that the array degradation is only about 2 percent after 5 years, a substantial improvement. Figure 5 expands on this result by illustrating the anticipated degradation in subsequent years and the result of different numbers of series blocks per branch circuit.

Module Yield Considerations

In addition to controlling array degradation, circuit redundancy features are also effective in improving module yield losses due to broken cells and other circuit failures which cause a module to be rejected during final assembly, shipping, and installation. A common module

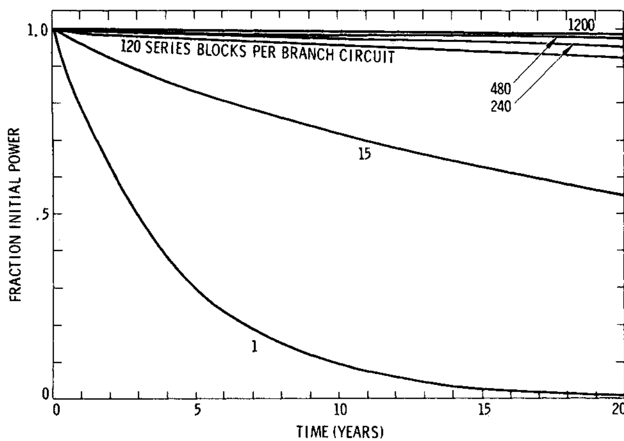

Fig. 5. Array power degradation vs time for a constant yearly cell failure rate of 0.01% for 8-parallel-string branch circuits with bypass diodes.

failure criterion is based on controlling electrical mismatch in the array and stipulates that a module is rejected if its power loss is greater than 10 percent of the average peak power output for all modules. Figure 6 displays the dependence of module yield computed for this failure criteria as a function of module series/paralleling, for three sizes of modules, and for a cell failure probability of 0.1% [10]. Considering the two 144-cell modules used in the previous example, interpolating in figure 6 gives a yield of 87 percent for the single-string module, and a much better 99 percent for the module incorporating 8-parallel cells by 2 series blocks.

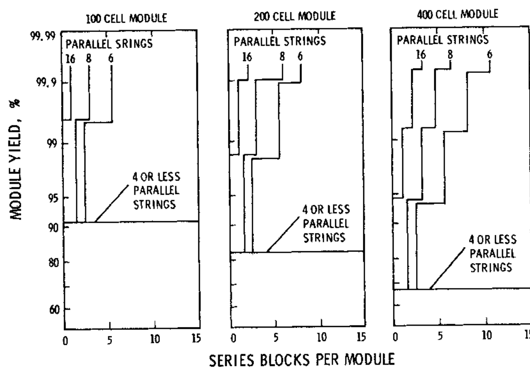

Fig. 6. Module yield versus series/paralleling assuming 0.1% cell failures and module rejection for power loss greater than 10%.

Hot-Spot Heating Considerations

A third subject related to array fault tolerance is the levels and effects of local cell hot-spot heating which can occur when a cell or group of cells is subjected to a current level which is greater than the cells short circuit current. As shown in figure 7, this condition can be caused by a variety of circuit faults such as cell cracking, local shadowing, and open circuiting of series/parallel connections. When the degree of heating exceeds safe levels (100 to 120°C in most modules) the module encapsulant system can suffer severe permanent damage [11]. Such damage has occurred in a

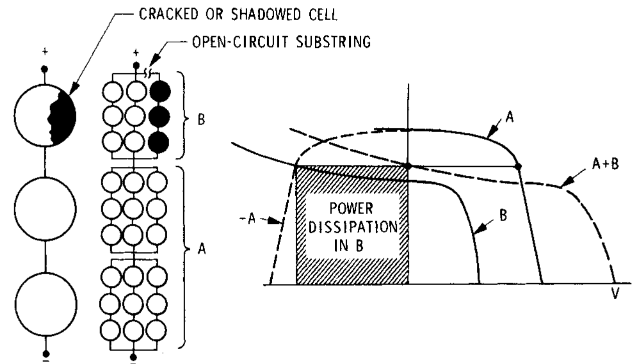

Fig. 7. Visualization of hot-spot cell heating.

variety of present-day large application experiments and strongly suggests the use of by-pass diodes or other corrective measures to limit the maximum heating level. References 10 and 11 describe means of determining the number of by-pass diodes required and test methods to verify that hot-spot heating is limited to safe levels. For most cell and module constructions, a by-pass diode is required around every 10 to 15 series cells.

COST-OPTIMUM REPLACEMENT STRATEGIES

Although circuit redundancy can substantially reduce array degradation associated with sporadic cell failures, module replacement is an additional strategy that can accomplish the same goal. One means of selecting the optimal maintenance/replacement strategy and level of circuit redundancy is based on minimizing the life-cycle energy cost of a photovoltaic system. Following my previous work the optimization can be formulated by setting the life-cycle benefits equal to the life-cycle costs including module replacement [12, 13]. The optimum system design is then found by minimizing the breakeven cost of the photovoltaic energy:

$$W = \frac{C_0 + \sum_{i=1}^{L} C_i M_i (1+k)^{-i}}{\sum_{i=1}^{L} E_i (1+k)^{-i}}. \tag{2}$$

W cost (worth) of energy
E_i energy generated in year i
C_0 initial plant cost
C_i cost per module replacement action in year i
M_i number of modules replaced in year i
k annual discount rate
L plant lifetime (20 years)

Eq. (2) allows a direct tradeoff between the effects of array degradation versus time (E_i), the module initial cost (C_0), and the cost of module replacement ($C_i M_i$). To properly account for the effect of inflation, all cost terms should be expressed in constant monetary units such as constant 1980 dollars, and the discount rate should be chosen accordingly.

To explore the general cost effectiveness of module replacement it is instructive to apply the above methodology to the 1000 V large ground mounted array considered in the previous examples. For a typical array and balance-of-system costs and efficiencies [13] and a cell failure rate of 0.01% per year, we can calculate the breakeven life-cycle energy costs for various redundancy and replacement options using (2). Figure 8 displays the calculated life-cycle energy costs for two replacement strategies as a function of the number of series blocks in branch circuits composed of 8-parallel × 2448 series cells. In the first strategy no module replacement is allowed and it can be seen that the life-cycle costs increase sharply with low numbers of series blocks. This reflects the rapid array degradation exhibited in figure 5 for these circuit configurations. For the second (dashed) curve in figure 8, modules are replaced each time a solar cell fails during the 20-year life of the plant. This results in no power degradation, but does cause a substantial module replacement-cost. This cost also varies with the number of series blocks due to reductions in module yield costs which occur when module series/paralleling achieves 8 parallel by two or more series blocks. This degree of module series/paralleling is only reached in this example when 272 or more series blocks are used per branch circuit.

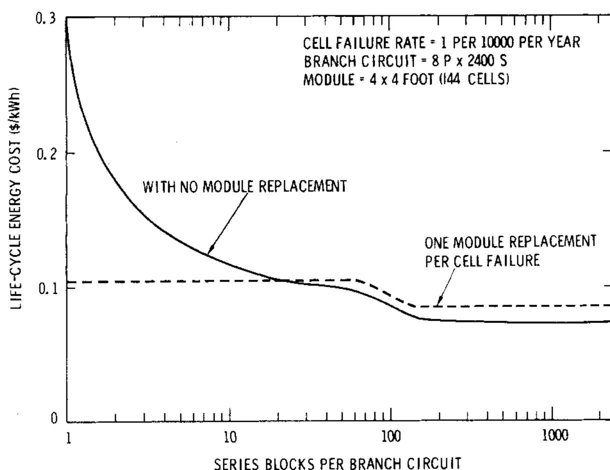

Fig. 8. Life-cycle energy costs for 8-parallel-string branch circuits.

As seen in figure 8 the optimum maintenance strategy depends on the degree of series/paralleling. When low degrees of series/paralleling are used, the least-cost maintenance strategy is to replace the affected module each time a solar cell fails. On the other hand, when a high degree of series/paralleling is used, the least cost strategy involves no module replacement. Only in a very small region where the two curves cross is a partial-replacement strategy optimum. When considering figure 8 it is apparent that the optimum configuration for an array of 4 by 4 foot modules in 8-parallel-string branch circuits is 272 or more series blocks, with no module replacement.

Figure 9 expands the parametric study to include the effects of other choices for the number of parallel strings - in this case 1 and 4 strings in parallel. In this graph, only the optimum-maintenance (least life-cycle) cost is plotted for each number of series blocks per branch circuit. The number of parallel strings has little influence on the conclusions relative to the optimum number of series blocks, or the optimum maintenance strategy.

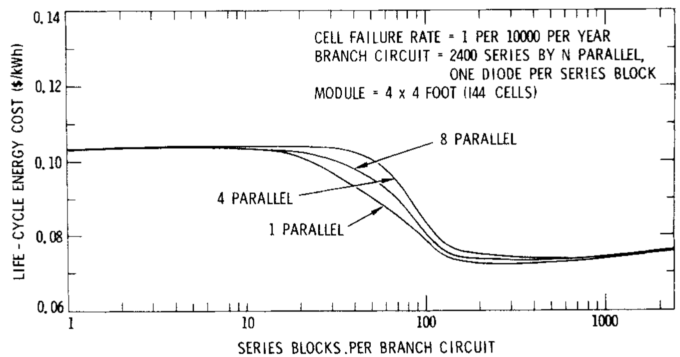

Fig. 9. Minimum life-cycle energy cost with by-pass diodes.

CONCLUSIONS

Cell failure rates as low as 0.01% per year can significantly degrade array performance if appropriate circuit redundancy is not applied. Several statistical design approaches address the areas of cell breakage, interconnect fatigue, glass breakage, and electrical insulation breakdown. The thesis of these methods is to design quantitatively for a specified low level of component failures, and then to control the degrading effects of the remaining failures through the use of fault tolerant circuitry and module replacement.

ACKNOWLEDGMENT

This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the US Department of Energy through agreement with the National Aeronautics and Space Administration.

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Ron Ross is Engineering Sciences Manager of the Flat-Plate Solar Array Project and supervisor of the Solar Photovoltaic Engineering Group at JPL. The major emphasis of his group's activities is on the development of reliability engineering design and test methods for terrestrial photovoltaic modules and arrays. During his previous years at JPL he has led various research and development activities involving advanced electrical/mechanical/thermal subsystems including large deployable solar arrays, high temperature solar arrays, ion-propulsion engines, power conditioners, propellant tanks and science instruments. He received his Doctor of Engineering degree in mechanical design at UC Berkeley in 1968 following his MS degree at the same university in 1965.

Manuscript TR81-155 received 1981 April 10; revised 1981 August 15.

★★★

Book Review

Ralph A. Evans, *Product Assurance Consultant*

The Maximum Entropy Formalism

Raphael D. Levine, Myron Tribus, Editors, 1979, $25.00, 498 pp.
MIT Press; 28 Carleton Street; Cambridge, MA 02142 USA.
ISBN: 0-262-22080-1; LCCCN: 78-10799.

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A new look at the relation between information theory and search theory □ J. G. Pierce 64 pp
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Generalized entropy, boundary conditions, and biology □ J. Rothstein 46 pp
The Gibbs grand ensemble and the eco-genetic gap □ E. H. Kerner 8 pp
Toward a mathematical definition of 'life' □ G. J. Chaitin 21 pp

This book is a collection of papers presented at the Maximum Entropy Formalism conference held at the Massachusetts Institute of Technology during 1978 May 2-4. The papers cover the background, principles, and some applications of the formalism of maximum entropy. The topic has little connection with the reliability discipline except that a) in the 1960s there was an attempt to show that the exponential distribution was *the* distribution for life under certain constraints, and b) attempts have been made to relate various concepts of entropy to uncertainty, and uncertainty is what reliability engineers have lots of.

My only quibble with the formalism is that there is often another arbitrary assumption tucked in, viz., statistically expected values, such as the mean and variance, are used as constraints. It is interesting that those constraints and the maximum entropy formalism can reproduce some basic equations from physics.

Two very interesting papers, by Jaynes and by Cox — two of the early workers in this field, make up about the first third of the book. If you're interested in the vagaries of mathematics, those two papers alone are worth the book. And — there is an attraction by the ideas in the book. Perhaps someday someone will usefully apply them to the reliability discipline — I hope so.

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