

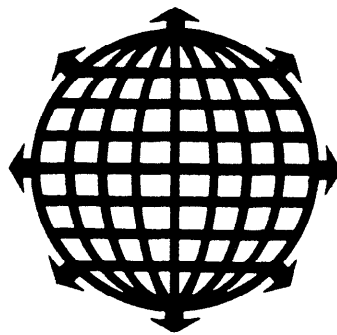
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SIMULATION-BASED RATINGS FOR SOLAR HOT WATER SYSTEMS

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ABSTRACT

The Solar Rating and Certification Corporation (SRCC) has promulgated a new standard, SRCC-OG300, for the rating and certification of solar hot-water systems (SHWS). This paper explains and exemplifies the rating process being used by SRCC. Standard performance indices are computed using a component simulation model (TRNSYS). There are two paths available: 1) **component test**, where all component models and the system model have been well validated and the component inputs are well defined, producing a "literal" simulation model; and 2) **system test**, where some components are not well modeled, the system model not validated, or the component inputs not well known, producing a "calibrated" simulation model. Component modeling assumptions and key uncertainties are discussed. The process is instantiated by an integral collector storage system rated using the system test path.

1. INTRODUCTION

The Solar Rating and Certification Corporation (SRCC) has promulgated a new standard, SRCC-OG300 (1), for the rating and certification of solar hot-water systems (SHWS). The goals of this standard include increasing system quality assurance and reliability, ensuring safety and health, lowering system and certification costs, and providing more useful ratings (2). The OG300 standard was implemented in March 1992, and has been applied to about 60 systems as of this writing. It has been adopted by the Sacramento Municipal Utility District as a prerequisite for entering their SHWS rebate program, enhancing quality and reliability and providing a sound basis for their performance-based rebates. The SRCC rating process, which is the focus of this paper, is thus part of a broad program supporting and helping to expand the SHWS industry.

A rating consists of specified quantitative indices of system performance under specific environmental and usage conditions (3). Before 1992, SRCC ratings were energy savings derived directly from an ASHRAE-95 test (4) using "average day" conditions defined in SRCC-OG200 (5). This is an indoor test (repeated until measured daily energy totals converge), specifying an irradiance profile from a solar simulator, constant ambient temperature, and a diurnal energy draw pattern. Although it provides a good framework for relative assessment of performance, applicable to any system and requiring no interpretive data analysis, the process has several shortcomings. The test is expensive: it's nominal, direct costs are about \$5K per system, and it's needed for each system *and* model not covered under a narrow component substitution policy. Requiring special facilities, the manufacturer could not know his "rating" until the system was submitted, and was thus effectively discouraged from any system optimization process. The rating does not provide utilities and owners long-term energy savings at their site under their use conditions, which is the relevant information for a cost/benefit analysis. Also, this rating process could not help utilities to determine demand savings.

The current SRCC-OG300 rating process overcomes these limitations and provides a number of other benefits. The rating is based on dynamic simulation with a validated, component-based numerical model. The fundamental premise is that when validated component models (whose inputs are based upon component measurements) are assembled into a validated system model, the simulation can adequately predict system behavior under a range of conditions. The simulation TRNSYS (6) was chosen for this purpose, as its modular and user-adaptable structure allows application to an unlimited range of system types, and it has a long history of validation. Once a model is established, a rating can be derived for a wide range of

scenarios (e.g., annual, "average day," and peak demand). Since the simulation of an additional SHWS of the same type and configuration (with variations such as collector area or tank volume) is very simple; ratings can be done for similar models at reduced cost. Also, the manufacturer can specify "component substitutions," i.e., alternative, nearly equivalent components that allow manufacturers to choose amongst those components as their availability and costs fluctuate. The simulation is then done with that component which gives the lowest performance. Another advantage of the simulation approach is that the manufacturer can use the models to optimize system design for the rating or application desired before submitting an OG300 application.

The concept of a simulation-based rating presents a number of issues that have been addressed by SRCC and are discussed in this paper. A process for obtaining a model must be available for *any* system type, including systems having components not well modeled or characterized. Inevitable innovations guarantee that validated models will never exist for every system that can be submitted for rating. A two-path process addressing this issue is presented in Section 2. The data needed for simulation inputs must be carefully defined, and is discussed in Section 3. To establish credibility, the simulation must be validated with demonstrated bounds on the model error, as discussed in Section 4. A consensus on an acceptable error bound must be based upon practical needs and realistic limitations of available methods. SRCC is attempting to achieve a root mean square accuracy of 10% or less for its simulation models. An example of a rating is given in Section 5. Conclusions are then listed.

2. RATINGS OVERVIEW

A general overview of the SRCC rating process is shown in Fig. 1. When SRCC receives an application for rating and certification, it is first screened for appropriate technical data (which are turned into model inputs) and other information, and then passed to a three-man design review team. The design review first ensures compliance with the SRCC-OG300 standard, and then defines the path to obtain the system simulation model and identifies any potential problems to be examined via simulation or other approach. As shown in Fig. 1., there are two paths for deriving the simulation model: 1) the **component test path** and 2) the **system test path**. Both paths incorporate our best physical modeling capability and knowledge of the system within the system model, as opposed to "black box" methods (e.g., (7)) in which *all* model parameters are considered unknown *a priori* and obtained from experiment.

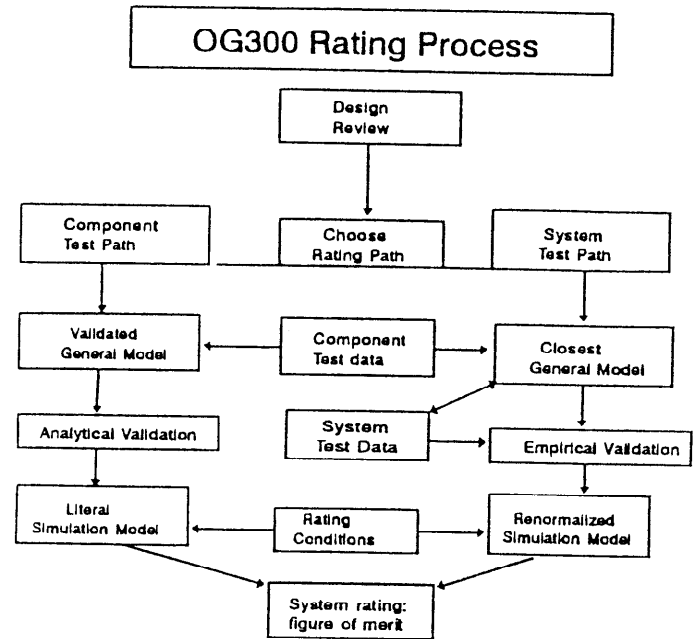


Fig. 1. Alternative paths in SRCC-OG300 for deriving the system ratings. The **component test path** is used when a well validated model exists, and otherwise the **system test path** is used.

The **component test path** is chosen if acceptable test data are available for all key system components, and if there is sufficient confidence that the model will be sufficiently accurate. The submodels for *each component* must have been previously tested and validated, and the *system model* (consisting of the coupled component models) must also have been validated. The resulting model is called a "literal" or "white-box" model, in that it is considered to literally represent the system on a component-by-component basis, with no significant uncertainty in key modeling or inputs. A "generic" drainback system, for example, (discussed in section 4) would be rated on the component test path. This path is used for "standard" systems whose modeling is well established.

The **system test path** is chosen when there is significant uncertainty concerning appropriate inputs for a key component submodel, when some aspect of one or more of the component models is considered uncertain, or when the system model has not been well validated. The system is first modeled to the fullest extent possible, developing a "best guess" or audit simulation model. A system test is then performed, and the system model is then adjusted to "fit" the experimental data, a process called model

renormalization. The renormalized model can be called an "equivalent" or "grey box" model, in that several of the many system parameters are treated as unknown and are determined via regression on measured performance data, with remaining parameters derived from *a priori* knowledge of the system. An integral collector storage system, for example, would be rated on the system test path because complex absorber-storage heat transfer mechanisms involving natural convection in an enclosure are not modeled, and because significant uncertainty may exist in modeling the system optics (e.g., tubular optics). An example is given below. It is also necessary to validate that the renormalized model adequately predicts performance over the anticipated range of rating conditions. Generally, passive systems and systems with innovative components use the system test path.

Validation of these derived models is clearly a key issue. The system test path presents additional conceptual issues. First, there is the question as to what system test data should be used for model renormalization. An SRCC-200 test can be and has been used, although this test is an inefficient means to renormalize a simulation model. Tests designed specifically for stable, repeatable model renormalization are not well established. A strawman SRCC standard (8) defines necessary ranges of conditions (high and low solar irradiance and temperature difference) needed within the data set used for the renormalization. Second, given the potential range of systems and models with their different parameterizations, there is the question as to how the model is to be renormalized. In (9), it is demonstrated that a single very simple equivalent model with a single optical gain parameter fitted to the SRCC-OG200 test result can be used for some rating purposes without undue error. A model-independent renormalization method based upon scaling the major *heat flows* generated from the system-specific audit model has been proposed for use in rating and field monitoring (10).

The model resulting from either path is then used to determine the system rating. For listing in the SRCC Directory of Rated System (11), the model simulates performance on an "average day" with conditions the same as for the SRCC-200 test (4). A check is always made whether the system will meet minimum draw temperature (45°C or 131°F) during all draws, as required by SRCC-OG300 (1). It is worth noting that this rating definition is mostly unchanged from the past; it is, however, derived from a simulation rather than an indoor test. Annual performance is currently determined for those sites where performance-based incentives are in place, such as for the Sacramento Municipal Utility District and for the South Coast Air Quality Management District. SRCC is

considering future adoption of a performance map covering the entire United States, printed on an approved "appliance label" similar to existing nonsolar hot-water-tank labels (2). The simulations have also been used to determine at a specific site whether the system will be subject to freezing, overheating, or produce underheated water. Uncertainties for freezing and overheating include the weather sequences and pass/fail criteria that should be used in these assessments. Methods for simulating diversified demand reduction are under development (12).

3. COMPONENT TEST DATA AND COMPONENT MODELS

Components significantly influencing system performance include collectors, tanks, heat exchangers, and pumps. Collectors are the major performance determinant, and present the least problem. All collectors are to have been tested via ASHRAE-93 (13) and listed in the SRCC Ratings book, unless the system test path is used. Model flow rates have been assumed to be those recommended by the collector manufacturer, although standard engineering piping system analysis will be implemented by SRCC in the near future. Specifications for all component test data needed are incomplete and evolving. A data base of standard component specifications is being generated for use by SRCC rating labs, but contains many gaps. For example, pump and controller electrical power and pump-system thermal interaction should be measured and available in the data base; it is difficult to obtain this data.

Heat exchangers have proved to be the most difficult component to model. Fortunately, the current SRCC systems are mostly sensitive below 10% to uncertainties in heat exchanger model (14). Although marginally acceptable, this uncertainty must be reduced to not compromise desired accuracy goals. Doubly pumped heat exchangers should be and have been tested at flow rates "close" to those used in the model (15). Methods for adjusting these data to other flow rates have not been implemented. Natural convection heat exchangers (immersed coils, wrap-around coils, and sidearm) are more difficult. Limited data exist, and, whenever possible, forms the basis for the heat exchanger-tank model. Manufacturers have been encouraged, in some cases, to supply additional data to temporarily fill this gap until third-party data can be obtained. In addition, the current TRNSYS models for heat exchangers are not directly applicable to natural convection devices, requiring engineering judgment or special study to "fit" the existing model to the device even when data are present. Projects are underway to generate fundamentals-

based, sound models for natural convection heat exchange (12,15).

Tank heat loss data and analysis indicate that the expected thermal loss coefficient (UA) based upon R-value of the insulation underestimates tank losses by about a factor of two. The explanation is presumably thermal shorts and single-pipe thermosiphoning. At present, SRCC is assuming that the nominal tank R-value is effectively halved. A project is underway to improve storage tank thermal models (16). Piping heat loss is similarly uncertain, because of uninsulated elements such as valves, pumps, and expansion tanks. Calculations indicate that these uninsulated elements increase heat loss from 50 to 200%. Currently, SRCC is assuming that these and other factors halve the effective R-value of the total piping system.

4. VALIDATION

An essential element in simulation-based rating is the process of validating the component and system models. "Validation" is a concept somewhat like "truth" in that it's uncertain what is meant, and it's certain one will never completely answer all questions. A well-founded adage bears repeating: "The only one who believes a simulation is the modeler; the only one who doesn't believe an experiment is the experimenter." One can distinguish three broad categories of validation (17): 1) **analytical**: the simulation is compared to a mathematical solution of the set of coupled equations it is supposedly solving; 2) **comparative**: the simulation is compared to other simulation(s) solving (hopefully) the same problem; and 3) **empirical**: the simulation is compared to measured system performance when driven by the same independent variables as the experiment. Analytical/comparative validation focus on detecting input errors and simulation "bugs." Empirical validation is much broader and much more difficult, involving the key issue of the physical reality or validity of the component and system models.

Some comparative validation has been done on SRCC models, by comparing them to FCHART (18). Average deviation between TRNSYS and FCHART for five system models was about 3% (12). Because FCHART was derived from TRNSYS runs, this check is for gross input errors only. It has been proposed (19) to do analytical and comparative validation on a series of simple steady-state and sinusoidal problems where the solution of the coupled algebraic equations can be derived from available equation-solvers.

Many empirical validation studies have been done over the years with different TRNSYS simulations for different system types. In (20), for example, a study was done comparing TRNSYS models to results of an OG200 test on a range of similar drainback systems. A two-level half-factorial experiment was run on five factors for a "generic" doubly pumped drainback system, including collector area, collector and tank flow rates, and drainback plus heat exchanger tank. The RMS deviation between measured and predicted auxiliary energy was about 3%, with maximum deviation about 8%. This level of accuracy is within desired error bands. On the basis of these and other studies, the SRCC design review team has rated such drainback designs on the component test path. A strawman SRCC standard for empirical validation has been written (21), which essentially specifies the range of conditions on environmental and draw variables during the test, and the criteria of acceptable comparison. Studies testing and refining this standard are underway at two locations.

Field monitoring studies aimed in part at comparing SRCC TRNSYS models with actual field performance are planned for the near future. System monitoring will be done for at least one year on twelve systems in New York, and TRNSYS models will be compared to actual performance on a subset of the data (22). A project using short-term field monitoring (instrumentation in place at each site for about a month) is being planned by the U.S. DOE in cooperation with a utility (23).

5. SYSTEM TEST PATH EXAMPLE

A series of similar integral collector storage (ICS) systems were rated on the system test path (24). The chosen equivalent model centered around a TRNSYS ICS module, which accounts for optical gain and thermal loss in a simplified manner. The module accounts for sky infrared losses and for draw-induced stratification. An incidence angle modifier (IAM, ratio of off-axis to normal incidence transmission-absorption product) map was used to model system optics. The map was predicted from a detailed Monte-Carlo ray-trace study on the system (25). System tests at two locations served as the data to renormalize and validate the system model.

Model renormalization was based upon two indoor SRCC-OG200 tests, done for a two module system and for a three module system. The solar simulator irradiance was always normal to the modules, and the SRCC irradiance profile was adjusted during testing to include an estimated IAM factor. First, the heat-loss coefficients of the ICS units were set to the results measured in indoor overnight cooldown tests.

Second, the two and three module TRNSYS models were configured to run exactly as the tests were done, and the normal incidence optical gain parameter $F_r(\tau\alpha)_n$ was adjusted in both cases to exactly match the actual Auxiliary energy obtained from the OG200 tests. It was shown (24) that a three-module model derived from the two-module renormalized model by multiplying all area-dependent inputs by 3/2 predicted the actual test data for the 3-module system within 2%. (The three-module model actually used for rating was based upon the independent fit to the three-module system test data.) A one-module model was derived from the renormalized two-module model by dividing all area-dependent inputs by two.

Validation of these models was done by comparing the renormalized models to two independent data sets. First, the two and three-module models predicted the result of four separate indoor one-day warmup tests to an average of 3%. Second, the two-module model was compared to three days of outdoor data at the Florida Solar Energy Center, with specified volume draws taken three times daily. The model predicted the total energy delivered to within 2%.

The models were then used to provide ratings and some overheating evaluation for the systems. First, SRCC-OG300 ratings were simulated. The incidence angles, draw energy, and auxiliary set point specified in (1,5) were simulation inputs. Second, annual ratings in the Sacramento area were calculated. The simulations also indicated that the system would tend to overheat in summer, consistent with field observation. (The overheating issue was clearly identified from the simulation only after the problem surfaced in the field, exemplifying the clear need to couple the simulation exercises with field observation.) When the manufacturer responded to this problem by introducing alternative designs, the new designs needed to be evaluated and rated. Since the change was external to the ICS modules and relatively simple to model (a pumping loop between ICS and auxiliary tank was added, based on several control strategies), the design review team allowed evaluation and rating without additional testing on the modified system.

6. CONCLUSIONS

The simulation-based rating process has proven to be a workable method for producing SHWS ratings. Although validation studies are far from complete, validation to date has indicated that the TRNSYS simulation provides answers within desired error bands. The method is very cost-effective for those systems having established models and on the component test path. The system test path will be

more expensive than the component test path, and standards-based procedures are not currently in place. Initial results indicate that the necessary test data can be taken outdoors and can be replicated by the manufacturer.

Future work includes ongoing projects and projects not yet begun. The studies underway to develop improved component models (natural convection heat exchangers, auxiliary tanks, photovoltaic controller modules) will be completed in 1993. Work to refine and establish system test and model validation standards will be followed by the slow process of formal consensus standards. Practical methods for determining diversified coincident demand reduction will be available for utilities and other users. Definition of a sound procedure for assessing freeze protection and overheating problems is important to heighten user confidence. Field monitoring projects now starting will be completed in 1994 time frame, and undoubtedly other field monitoring projects will be initiated as utilities consider SHWS as a demand-side management measure, with concomitant evaluation criteria to be satisfied. These studies will contribute greatly to our further understanding of the strengths and weakness of the SHWS simulation process.

7. ACKNOWLEDGMENTS

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