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OVERVIEW OF THE ASHRAE TC 4.7 ANNOTATED GUIDE TO MODELS AND ALGORITHMS FOR ENERGY CALCULATIONS RELATING TO HVAC EQUIPMENT

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ABSTRACT

An annotated guide to 652 references containing mathematical models and computer algorithms for calculating the energy performance of HVAC equipment has been developed (ASHRAE Research Project 530-RP). The literature reviewed consists mostly of easily accessible references that represent the most current information available in North America and Europe.

The guide is primarily aimed at practicing engineers who wish to develop their own simulation programs for analyzing the energy usage of HVAC equipment in buildings. The user can read the front matter of the guide to understand the differences in simulation approaches found in the literature, and their limits of applicability. Then, for a particular equipment type, the user can consult the relevant section of the guide to select the references pertaining to the particular approach of interest.

INTRODUCTION

The need for easily accessible information about simulating the energy performance of HVAC equipment is increasing as microcomputer capabilities in engineering offices improve. Although there already are a large number of packaged energy analysis computer programs, many practicing engineers develop their own programs to simulate novel HVAC systems or to study project-specific problems. However, there is no consolidated source of information documenting the mathematical models and computer algorithms that are available in the literature. Thus, significant effort is often expended in searching for this technical information.

ASHRAE has offered the publication *Energy Calculations 2—Procedures for Simulating the Performance of Components and Systems for Energy Calculations* (ASHRAE 1976) in an earlier effort to help those developing programs to simulate HVAC equipment energy usage, but this is now out of date. To improve this situation, ASHRAE TC 4.7 has sponsored research (ASHRAE Research Project 530-RP), which is reported here.

The objective of this work was the preparation of an annotated guide to literature that contains mathematical models and computer algorithms for calculating the performance of HVAC equipment. The annotated guide (Yuill 1989) is a stand-alone document that facilitates access to these published algorithms and models. It is the first step in ASHRAE's development of a series of publications providing technical information on how to simulate HVAC system components. These publications will be aimed at assisting engineers who are attempting to develop their own HVAC system simulation software, although they will also be useful to others with different purposes.

The annotated guide is primarily aimed at practicing engineers who wish to develop their own simulation programs for analyzing the energy usage of buildings. However, it is also aimed at those who wish to carry out dynamic analyses of equipment performance, and at those who wish to carry out detailed, component-by-component simulation for the purpose of optimizing the design of this equipment. Therefore, the focus of the guide is on steady-state and "quasi-steady-state" algorithms and models, but dynamic ones are also considered.

In the annotated guide, the models and algorithms that have been described in the literature are categorized according to equipment type, and are characterized as to approach and limits of applicability. Equipment for all types of buildings from residences to large office buildings is included.

OVERVIEW OF THE GUIDE

Definitions

Several words that are generally given a range of interpretations are defined here so they can be used with more precision in this paper. These are:

1. Model: A model focuses on the physical laws and relationships governing the process or device to be simulated, not on the computational steps in the simulation. It is usually expressed in mathematical notation. It usually can be inverted to treat any of the parameters and variables it contains as the independent ones. A model is developed by analysis from known physical laws or empirical relationships, or is deduced by experiment.

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2. Algorithm: An algorithm is a computational technique for the solution of a problem stated in a model. It has a single narrow purpose and consists of a number of specifically defined steps. While a model may specify the relationship between a number of parameters and variables without defining which are the controlling variables in a particular case, an algorithm proceeds from a particular set of specified "input" parameters and variables to a particular set of "output" variables. Thus, a particular model might be embodied in several different algorithms for use when different sets of parameters and variables are known. An algorithm will have a specific range of parameter and variable values for which it is applicable. It can be expressed in English, in mathematical notation, in a graphical representation such as a flow chart, or in pseudocode, which follows the general format of common programming languages, but which allows more flexibility in the use of commonly recognized symbols and notations than a particular language.
3. Steady-state model: A steady-state model is applied once per time period (normally an hour) and the input variables used all have values that apply at that particular time. Although the input variables may change from one time period to the next, the results obtained in each time period are independent of the previous values of those variables.
4. Quasi-steady-state model: A quasi-steady-state model is one in which an essentially steady-state calculation is done in each time period, but a value of a variable from the previous time period is used as a starting point. Such models are not used to try to simulate transient phenomena. Rather, they are used to allow a sequential calculation to be done in each time period instead of an iterative or simultaneous calculation.
5. Transient model: A transient or dynamic model is one that describes the time dependence of the phenomenon simulated. In an algorithm based on such a model, the controlling variables will include values from previous time steps.

Types of Algorithms and Models

Four classifications of models have been developed for the annotated guide to distinguish between the general approaches found in the literature. They are: (1) purely empirical, (2) semi-empirical, (3) semi-theoretical, and (4) fundamental principle. The same classifications have been applied to algorithms based on these types of models. Each of the following four sections describes one of these approaches, comments on its range of applicability, and provides an example to illustrate the approach.

Purely Empirical Algorithms and Models Purely empirical algorithms and models use a simple "black box" concept that ignores physical laws. The equipment is treated as a single unit. No information is required about the interactions between the equipment components, or about the physical dimensions, properties, and processes that determine the behavior of the equipment.

Analysis of variance, regression analysis, and intuition are used to select input variables that are important in representing equipment performance, and to develop the form of the equations that directly relate the input variables to the desired output variables. Regression analysis is used to fit the equations to discrete performance data obtained from the equipment manufacturer, from laboratory tests, or from more detailed models.

The algorithm or model can be used to predict equipment performance within the range of available test data for the particular equipment operating in a specific environment. However, it cannot be used to predict performance outside this range of test data, or for other similar types of equipment operating in different environments. Different equation coefficients, or even different equation forms, must be developed for each individual piece of equipment that is simulated. This feature severely restricts the flexibility of this approach in building energy analysis calculations.

To illustrate this approach, consider the simulation of a water-cooled liquid chiller operating in a particular building located in a dry climate. An inspection of performance test data for the chiller indicates that its power consumption varies only with outdoor air temperature, according to a quadratic polynomial. The three coefficients of the equation are determined using the least squares method. Although the model can simulate the performance of the chiller under the specified conditions, it does not directly account for intermediate parameters, such as the impact of changes in building thermal resistance or thermal mass on the cooling load, which affect the chiller's performance. Thus, another model would need to be developed if the same chiller were placed in a different building.

Semi-Empirical Algorithms and Models Semi-empirical algorithms and models use a "black box" concept that is supported by physical laws. The equipment is treated as a single unit. No information is required about the interactions between the equipment components, or about the physical dimensions and properties that characterize the equipment. However, some knowledge of the physical processes that govern the behavior of the equipment is required.

Analysis of variance, regression analysis, and intuition, aided by a knowledge of general engineering principles, are used to select input variables that are important in representing equipment performance, and to develop the form of the equations that directly relate the input variables to the desired output variables. Regression analysis is used to fit the equations to discrete performance data obtained from the equipment manufacturer, from laboratory tests, or from more detailed models.

The algorithm or model can be used to predict equipment performance within the range of available test data for the particular equipment. Performance predictions can also be made for other similar types of equipment operating in similar environments, but it cannot be used to predict performance outside the range of available test data. The simplicity and flexibility of these algorithms and models make them particularly well-suited to simulating complex devices (such as chillers) in building energy analysis calculations that use hourly time steps. However, for simpler devices such as heating coils or air-mixing systems, it will usually be possible to take a more theoretical approach.

To illustrate this approach, consider the simulation of a water-cooled liquid chiller. From fundamental principles of the operation of vapor-compression machines, it can be deduced that the capacity and coefficient of performance (COP) of the chiller are functions of the temperature of the water leaving the liquid cooler and of the temperature of the water entering the condenser. Also, since chiller capacity modulation can be achieved through processes such as cylinder unloading, the fraction of full-load power consumption must be a function of chiller capacity. Quadratic equations can be developed to relate the capacity and COP to the water temperatures, and to relate the fraction of full-load power consumption to the capacity. The least squares method can be used to fit these equations to performance test data. In addition, variables can be normalized by their nominal values so that different chillers of the same type can be simulated using the same equations and coefficients.

Semi-Theoretical Algorithms and Models Semi-theoretical algorithms and models rely more on fundamental physical laws, but may use empirical expressions for evaluating coefficients, or may use the "black box" approach for simulating particular components of the equipment. Information is required about the interactions between the equipment components, and about the physical dimensions, properties, and processes that determine the behavior of the equipment.

Semi-empirical models are developed for two or more components based on discrete performance data obtained from the component or equipment manufacturers, from laboratory tests, or from more detailed models. General engineering principles such as conservation of energy and conservation of mass are used to develop relations that represent the interactions between the components. In some cases, semi-empirical correlations are used to represent an interaction between components to fill in gaps in the theory or to simplify the solution.

The algorithm or model can be used to predict equipment performance within the range of available test data for the particular configuration of components that comprise the equipment. The semi-empirical model for a particular component can be used to predict the performance for that component within the range of available test data for that component. Also, these semi-empirical models can be used to predict the performance of other similar types of components operating in similar configurations. However, equipment or component performance cannot be predicted outside the range of available test data for the configuration of components that comprise the equipment. This approach permits more simulation flexibility than the semi-empirical approach. This makes it useful for simulating relatively simple devices (such as heating coils) in building energy analysis computer programs that use hourly time steps. However, the increased level of detail in the semi-theoretical approach makes it less suitable for simulating more complex devices because this additional detail may result in the use of too much computer time or may require more input data than the user can provide.

To illustrate this approach, consider the four basic components of a water-cooled liquid chiller: the compressor (and its drive), the condenser, the refrigerant flow control device, and the liquid cooler. The heat transfer rates in the condenser and liquid cooler can each be represented by a simple energy balance on the water side, and by simple heat exchanger theory (LMTD concept). Equation fitting can be used to determine the overall heat transfer coefficient of each heat exchanger. To simplify the solution, the interaction between these two components can be represented by a semi-empirical correlation for the COP of the chiller. Then, given the cooling load on the liquid cooler, the water flow rates, and the water inlet temperatures, along with the definition of COP, the power consumption of the chiller can be determined, as can the tower load, refrigerant temperatures, and water outlet temperatures. In this case, no information is required about refrigerant properties, or about compressor or expansion device characteristics.

Fundamental Principle Algorithms and Models Fundamental principle or mechanistic algorithms and models do not use a "black box" concept. Instead, they use general principles of thermodynamics, heat transfer, mass transfer, and momentum transfer to predict pressures, temperatures, energy flow rates, and fluid flow rates to, from, and within each component of the equipment. Little or no performance test data are used, since most of the information required is obtained from physical descriptions of the equipment and its components. Sometimes, semi-empirical correlations are used to fill in gaps in the theory, such as for determining the refrigerant-to-tube-wall heat transfer coefficient in the liquid cooler.

Since few performance data are used as input to the algorithm or model, predictions of equipment and component performance are limited only by the range of applicability of the theories or correlations used in the simulation. In many cases, the algorithm or model is sufficiently detailed to permit studies of equipment dynamics or of component retrofits. However, for complex devices (such as chillers or boilers), this amount of detail requires numerous inputs, and programs that implement these algorithms or models tend to consume considerable amounts of computer time. Thus, this approach is of limited use for simulating these complex devices in building energy analysis calculations. On the other hand, there are simple devices that are easily described by fundamental equations and are best simulated by a purely theoretical approach. For example, an air-mixing system can be described by the laws of conservation of mass and energy, and these equations can easily be implemented in a building energy analysis program that uses hourly time steps.

To illustrate this approach, consider the simulation of a water-cooled liquid chiller. In particular, consider one component: the liquid cooler. Separate energy balances on the refrigerant and water flows through the liquid cooler relate refrigerant and water inlet and outlet thermodynamic states to the heat transfer rate in the liquid cooler. Simple heat exchanger theory (LMTD concept) relates the heat transfer rate in the liquid cooler to the refrigerant evaporation temperature and to the water inlet and outlet temperatures. The overall heat transfer coefficient of the liquid cooler is determined from the dimensions of the liquid cooler tubes, from the thermal conductivity of the tube walls, and from semi-empirical correlations found in the literature for convective heat transfer coefficients inside and outside the tube walls. With this model, the outlet conditions of the two fluid streams can be determined, if the following input variables are known: the cooling load on the liquid cooler, the water inlet temperature and flow rate, and the entering refrigerant state and flow rate. In this approach, the refrigerant state and thermal properties leaving the liquid cooler must be predicted because the refrigerant acts as a link between the liquid cooler and the compressor.

Organization of the Guide

In the annotated guide, annotations are brief because the organization of the guide itself provides the annotations. In this form, the user can read the front matter of the guide to understand the differences in simulation approaches and their limits of applicability. Then, for a particular equipment type, the user can consult the relevant section of the guide to select the references that pertain to the particular simulation approach of interest.

The format used in the guide to present the literature is as follows: (1) equipment name, (2) equipment description, (3) relevant handbook chapter, (4) key references, and (5) related references. A sample section of the guide (Liquid Chilling Systems) is included in Appendix A of this report to illustrate this format.

To aid users of the guide in locating the particular sections in which they are interested, equipment names have been ordered to match as closely as possible the established and familiar order used in the *ASHRAE Equipment Handbook* (ASHRAE 1988). For some equipment types, no relevant references were found, so these types of equipment are excluded from the guide.

Once a section of interest is found, users can read a description of the equipment type named in that section to clarify which specific pieces of equipment the references cited pertain to.

So that users of the guide can easily locate more information describing the equipment named, the relevant chapters in the series of ASHRAE handbooks are listed (ASHRAE 1985, 1986, 1987, 1988).

Users can then consult lists of key references and/or related references about the particular equipment type of interest. In general, these references represent the most current information available on equipment simulation, and are those that are well-known and easily accessible to anyone planning to develop a simulation program. However, references containing equipment simulation techniques that are improvements on the present techniques and/or that were found in locations that can be considered obscure from the perspective of a North American building energy system simulator have also been included in the guide. Only literature written in English has been reviewed.

In the guide, a list of key references is subdivided into one or more of the following eight parts: empirical algorithms, empirical models, semi-empirical algorithms, semi-empirical models, semi-theoretical algorithms, semi-theoretical models, fundamental principle algorithms, and fundamental principle models. These subdivisions are based on the definitions of algorithms and models and the description of types of algorithms and models given in the introduction to this paper. In some cases, less than eight subdivisions are used in the guide because references for all eight types of algorithms and models were not available in the literature.

Each list of related references consists of literature that does not contain specific models or algorithms. These references provide background information of interest to those who prepare equipment simulation programs, and/or they contain information on topics such as heat transfer correlations or methods of testing equipment. The references on testing are included because they provide good indications of the type of data usually available for input to energy calculations.

Although the annotated guide focuses on the development of simulation software for analyzing the energy usage of buildings, it is also aimed at those who wish to carry out transient or dynamic analyses of equipment performance. To distinguish between references containing steady-state or quasi-steady-state algorithms or models and those containing transient ones, an asterisk has been placed at the end of each reference to transient models or algorithms. A footnote regarding the meaning of the asterisk is printed at the bottom of every page for convenience.

A particular set of references that provides the best models and algorithms has not been recommended in the guide. All of the references that have been annotated contain useful models and/or algorithms. The decision of which model or algorithm is best for a particular application depends on the simulation approach the user is considering and on the application. Thus, this decision has been left to the user.

Key words for use in supplementary literature searches are not listed explicitly in the guide because it contains sufficient information in its present form for the user to select key words independently.

In the last section of the guide ("Fundamentals"), no annotations of the literature are provided. Also, descriptions are not provided to clarify subsection headings because they are self-explanatory. The references in this section all pertain to fundamental principle techniques used in equipment simulation.

ANALYSIS OF NUMBER OF REFERENCES REVIEWED

Table 1 shows the number of references we reviewed according to equipment category and model or algorithm type. For example, 44 references pertaining to air-cooling and dehumidifying water coils were reviewed. These references contained 5 semi-theoretical algorithms, 5 semi-theoretical models, 8 fundamental principle algorithms, and 18 fundamental principle models. Eight related references were found, but no references with empirical or semi-empirical algorithms or models were located.

The categories in Table 1 are listed in ranked order according to the total number of references reviewed in any single category. This ranking was used to facilitate analysis of which categories contain the most or least number of references reviewed.

It must be recognized that this ranking cannot determine which categories need further research because Table 1 only represents the references we reviewed, not all references that might be available. For instance, there probably is no need for more research regarding the simulation of steam turbines in building energy analysis programs, even though we located only two references pertaining to this subject. We attempted to prioritize our literature search efforts according to the importance we perceived of the equipment type in HVAC simulation programs. As Table 1 shows, there are many references reviewed that pertain to the simulation of major components of a modern HVAC system. The categories in which few references were reviewed generally consist of uncommon equipment types (e.g., electrical input/thermal output heat storage devices), equipment used in restricted regions of North America (e.g., evaporative air coolers),

TABLE 1
Ranked List of Number of References Reviewed

Category	**Reference Type**										
	EA	**EM**	**SEA**	**SEM**	**STA**	**STM**	**FPA**	**FPM**	**RR**	**Total**	**Rank**
Air-Cooling and Dehumidifying Water Coils	0	0	0	0	5	5	8	18	8	44	1
Air-Heating Water Coils	0	0	0	0	3	8	7	17	6	41	2
Air-Cooling and Dehumidifying Direct-Expansion Coils	0	0	0	0	6	4	6	10	4	30	3
Direct-Contact Mechanical-Draft Cooling Towers	0	2	3	1	6	16	1	0	0	29	4
Air-to-Air Unitary Heat Pumps	0	2	8	11	0	0	1	1	5	28	5
Boilers	0	0	7	3	2	4	2	7	1	26	6
Controllers	0	0	0	0	1	14	1	3	3	22	7
Liquid Chilling Systems	0	1	11	4	1	1	0	1	1	20	8
General Heat Exchangers	0	0	0	0	2	7	0	8	3	20	9
Solar Collectors	0	0	3	0	2	8	0	2	5	20	10
Furnances	0	0	7	4	2	3	0	0	3	19	11
Heat Transfer in Pipes and Ducts (*)										19	12
Pressure Drop in Pipes and Ducts (*)										16	13
Valves	0	0	0	0	1	9	2	2	1	15	14
Centrifugal Pumps	0	0	7	4	1	0	0	0	3	15	15
Fans	0	0	5	5	0	0	0	0	4	14	16
Positive-Displacement Compressors	0	0	0	0	3	3	2	6	0	14	17
Sorption Dehumidification Equipment	0	0	2	4	0	0	2	5	1	14	18
Unitary Air Conditioners	0	1	2	1	5	0	0	0	4	13	19
Liquid Coolers (Evaporators)	0	0	0	0	2	2	1	5	2	13	20
Air-Cooled Condensers	0	0	0	0	1	1	4	7	0	13	21
Air-Heating Steam Coils	0	0	0	0	3	1	2	4	2	12	22
Water-Cooled Condensers	0	0	0	0	3	2	1	5	0	11	23
Humidifiers	0	0	0	0	3	2	1	3	2	11	24
Air-to-Air Energy-Recovery Equipment	0	0	0	0	3	1	0	4	3	11	25
Air-Diffusing Terminal Boxes	0	0	0	0	0	1	6	2	2	11	26
Air-to-Water Unitary Heat Pumps	1	0	4	2	0	1	0	0	2	10	27
Radiators	0	0	1	4	0	0	0	4	1	10	28
Psychrometrics (*)										10	29
Water-Tank Sensible Heat Storage Devices	0	0	0	0	1	0	0	5	3	9	30
Sensors	0	0	0	0	0	8	0	1	0	9	31
Refrigerant-Control Expansion Devices	0	0	0	0	0	1	1	5	1	8	32
Lithium-Bromide Water Absorption Air Conditioning Equipment	0	0	3	2	0	0	0	0	3	8	33
Direct-Contact Non-Mechanical-Draft Cooling Towers	0	0	0	1	2	5	0	0	0	8	34
Operators	0	0	0	0	0	5	0	2	1	8	35
Indirect-Contact Cooling Towers	0	0	0	0	2	4	0	0	0	6	36
Dampers	0	0	0	0	0	6	0	0	0	6	37
Evaporative Condensers	0	0	0	0	3	3	0	0	0	6	38
Ammonia Water Aborption Air Conditioning Equipment	0	0	2	1	0	0	0	0	3	6	39
Packed-Rock-Bed Sensible Heat Storage Devices	0	0	0	0	0	0	0	3	2	5	40
Ice-Storage Latent Heat Storage Devices	0	0	0	0	0	0	1	2	2	5	41
Engines	0	0	2	3	0	0	0	0	0	5	42
Equation Fitting (*)										4	43
Centrifugal Compressors	0	0	0	0	1	1	0	2	0	4	44
Indirect Evaporative Air Coolers	0	0	2	0	0	2	0	0	0	4	45
Room Air Conditioners and Packaged Terminal Air Conditioners	0	0	2	0	0	0	0	0	1	3	46
Direct Evaporative Air Coolers	0	0	1	0	1	1	0	0	0	3	47
Gas Turbines	0	0	2	0	0	1	0	0	0	3	48
Phase-Change-Material Latent Heat Storage Devices	0	0	0	0	0	0	0	1	2	3	49
Air Washers	0	0	0	0	0	2	0	0	0	2	50
Steam Turbines	0	0	0	0	0	2	0	0	0	2	51
Infrared Heating Equipment	0	0	0	1	0	0	0	1	0	2	52
Electrical Input/Thermal Output Heat Storage Devices	0	0	0	0	0	0	0	0	1	1	53
Unit Ventilators and Unit Heaters	0	0	1	0	0	0	0	0	0	1	54
Total:	**1**	**6**	**75**	**51**	**65**	**134**	**49**	**136**	**86**	**652**	

EA: Empirical Algorithm
EM: Empirical Model
SEA: Semi-Empirical Algorithm
SEM: Semi-Empirical Model
STA: Semi-Theoretical Algorithm
STM: Semi-Theoretical Model
FPA: Fundamental Principle Algorithm
FPM: Fundamental Principle Model
RR = Related Reference
(*) = Review did not subdivide into reference types.

and equipment that does not significantly affect the overall energy consumption of most large commercial or industrial buildings (e.g., room air conditioners).

It is interesting to note that there were almost twice as many references reviewed containing models as there were those containing algorithms (327 vs. 190). This substantial difference indicates that although we expect literature containing algorithms instead of that containing only models to be of greater value in facilitating the development of HVAC equipment simulation programs, we could not find many references of this type currently available to meet this need.

RECOMMENDATIONS FOR PREPARATION OF FUTURE ANNOTATED GUIDES

Since the annotated guide we have prepared only represents a "snapshot in time" of the currently available HVAC equipment simulation literature, it may be desirable to update and/or revise the guide at a later date when new references become available. In this case, we recommend that two important lessons we learned in this project be incorporated in the preparation of future guides.

First, the depth of the review should be extended at the expense of a reduction in its breadth. That is, more critical comments that characterize fewer references in greater detail would be desirable. The literature reviewed in any particular category would then consist of only three or four references containing the strongest models or algorithms. In addition, the number of categories considered could be reduced, so that only those references pertaining to the most commonly simulated equipment types would be reviewed in detail. Thus, less effort would be allocated to searching for new references, while more effort would be expended documenting the algorithms and models that are important to those developing HVAC equipment simulation programs.

Second, a standardized format for presenting models and algorithms in technical or symposium papers should be encouraged by ASHRAE. A common format in the literature would greatly reduce the time spent reviewing each reference so more critical comments could be produced, thus improving the utility of the guide.

CONCLUSIONS

A stand-alone annotated guide to 652 references containing mathematical models and computer algorithms for calculating the energy performance of HVAC equipment has been prepared. The literature reviewed consists primarily of easily accessible references that represent the most current information available in North America and Europe. The guide will significantly reduce the time spent searching for technical information required for the development of HVAC equipment simulation programs. It also provides a foundation for the preparation by ASHRAE of a series of HVAC component simulation guides.

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APPENDIX A

Sample Section of the Annotated Guide (Liquid Chilling Systems)

3.5 Liquid Chilling Systems

Equipment Description:

A liquid chilling system is a mechanical vapor-compression machine that cools a secondary coolant such as water or brine for air conditioning or refrigeration. Its basic components include: a liquid cooler (refrigerant evaporator), a compressor (and its drive), a condenser, and refrigerant flow-control devices.

Relevant Handbook Chapter:

ASHRAE. 1988. "Chapter 17, Liquid chilling systems." *ASHRAE handbook—1988 equipment.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

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