Dynamic Simulation Software as a Graphic Tool for Energy Efficient Building Design

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ABSTRACT

Building designers are increasing their use of computer software to more effectively take advantage of analytical tools that are useful to the design process. The area of energy analysis, though developing for twenty years or more, is still not effectively integrated into the conceptual design process. Too often, energy performance is evaluated as an after thought or it is done only for compliance to local energy codes. One reason that energy principles are ignored in design is that building designers are accustomed to communicating in graphical formats during the design process, and energy performance is typically represented in numerical formats. Energy results are often presented in tabular forms and are therefore hard to visualize by the designer.

This paper presents results of research that was intended to encourage energy considerations early in the design process through the use of dynamic simulation of energy results along with the pictorial representation of the building's physical form. The software allows a designer to dynamically simulate sun motion, shadow patterns, energy performance, costs, and thermal impacts on walls, windows, and roofs. Much of this is done in bar-chart format while sun motion and shadow patterns are done with animation. The program also permits the designer to interactively alter (through icon selections) wall materials, window types, occupancy parameters, lighting levels, and mechanical system types. Results of every parameter change are revealed graphically in real time animation.

Part of the research endeavor was to include design knowledge in a database that would help advise the designer on space layouts, material selections, and practical limitations on building features such as percent glazing and story heights. An energy knowledge base provides advice to the designer as to which building parameters would be most likely to improve the energy performance if modified.

The software operates on a Silicon Graphics workstation under the UNIX operating system and is developed in the C language. High resolution graphics is also an essential ingredient to beneficial use of the software.

INTRODUCTION

Energy consciousness during the design process is a critical factor for achieving responsible building design. Often times, however, energy strategy making is put off until the final stage of design when it is too late to have a major impact. Software tools are available to help with energy analysis for buildings, but most existing simulation models are too complicated to apply at the conceptual design stage. And, since energy principles are abstract and hard to visualize, designers are seldom successful in integrating sound energy principles into the building design. Though the language of graphics has long been the default for building designers, this capability is relatively new for computers. Now that computer graphics is becoming more common, there is real promise that energy concepts might be solved properly in the conceptual design stage.

The research reported here explores the concept of using computer graphics to support energy efficient building designs. It focuses on the visualization of building energy through a graphical interface in the early design stage. The main goals are:

- to facilitate description of a building's geometry through an integrated graphic input model,
- to apply computer graphics to the results end of the design loop, and
- to permit designers to visualize and understand energy conservation concepts.

This software model (ENERGRAPH) is a highly interactive graphical interface that will help designers in the following areas:

- creation of building layouts by using automated spatial synthesis algorithm,
- analysis, interpretation, and presentation of weather information for a selected location,
- dynamic simulation of the sun motion and its impact on the building envelop and orientation on any given date,
- dynamic analysis of energy performance, and
- real-time energy feedback in various graphical formats -- 2D and 3D images in animations.

DESIGN TOOL FLEXIBILITY

Any building design tool that is intended to promote energy-efficient design practices must not only have reliable algorithms for estimating energy use, it must also deliver methods for displaying energy efficiency concepts. It must clearly present the information to adequately describe the relationship of building design and energy performance and also show the structure under which this information is organized for decision making. Some of the major criteria for such a system are as follows:

1) The system must be flexible, permitting the designer to create or revise input by several methods.
2) The input processor should allow building layout and energy parameters to be easily modified.
3) The numerical information should be graphical where possible and should be in common formats.
4) The building energy performance should be available both in numerical and graphical formats.
5) All changes in building parameters should be analyzed interactively and dynamically.
6) All design input (both geometric and numeric) should be available in the energy analysis report.

Using the above objectives, the software tool has been divided into six parts. These are: 1) building geometric information, 2) building location and local climate information, 3) sun motion animation, 4) energy design parameters, 5) graphical energy performance feedback, and 6) on-line help sessions.

KNOWLEDGE DATABASES

The software system is developed around the concept of integrating "Object-Oriented Design" modules with a "Knowledge Database" to enable designers to create or modify floor plans easily and efficiently. Once the designers finish creating the building layout, all the related energy information will be automatically loaded from a default database into the system. Designers can either use the generated building layout and the default energy design parameters to instantly get an energy analysis or modify the building plan and its energy parameters. The feedback is immediate. The data base contains 13 building types, all of which contain unique default values; e.g., indoor temperature setting, HVAC system type, occupancy and lighting density, and fuel type. Samples appear in Table I.

Table I. Building types and default parameters.

Bldg. Type	ODF	PDF	VRF	SOG	TOG
Office	120	2.0	15	250	450
Education	50	2.2	12	250	454
Hospital	70	3.2	20	250	425
Clinic	100	2.0	20	250	450
Theater	10	0.8	15	230	350
Arena	15	0.8	15	250	500
Restaurant	30	4.0	30	275	550
Mercantile	30	2.4	15	250	500
Warehouse	1000	0.4	25	340	790
Hotel	80	2.2	20	250	450
Nursing Home	150	1.8	20	250	425
Residential	400	1.0	25	250	450
Other	100	2.0	15	250	450

Symbol key for table:
ODF=Occupancy density factor (sq.ft. per person)
PDF=Power density factor (watts per square foot)
VRF=Ventilation rate factor (cfm per person)
SOG=Sensible occupant gain (Btuh per person)
TOG=Total occupant gain (Btuh per person)

Along with each building type is also a default mechanical system configuration. Seven (7) HVAC configurations are assumed - four packaged and three central plant systems - and each of these has an air handling unit that would be typical for the type of building being designed. Along with each HVAC type is a default seasonal coefficient of performance (C.O.P.) and an air handler power demand in units of kw per 1000 cfm. Again, these defaults are displayed for the designer's information and can be altered at any moment at the discretion of the designer. These are shown in Table II.

Table II. Default HVAC systems with efficiencies.

System	Seas. C.O.P.	Fan Kw/ MCFM
Window DX unit	2.4	0.15
Thru-wall DX unit	2.1	0.15
Residential DX split system	2.2	0.3
<25 ton air-cooled roof-top	2.5	0.7
25-100 ton air cooled *	2.7	1.2
25-100 ton water cooled *	3.2	1.2
>100 ton water cooled *	3.4	1.75

* Systems with central air handling units.

For the heating systems, only the fuel type is defaulted. The delivery system is assumed to be the same as the HVAC type. Accompanying fuel types are fuel efficiency, heating value (Btu per unit), the name of the fuel unit (e.g., therms, kwh, gallons), and the fuel cost ($ per unit). Available fuels and accompanying parameters are shown in Table III.

Table III. Heating fuel types and parameters.

Fuel Name	Effi-ciency	Heating Value	Fuel Unit	Cost/ Unit
#2 Oil	0.7	139,000	Gallons	0.95
#4/#6 Oil	0.7	150,000	Gallons	0.95
Nat. Gas	0.75	100,000	Therms	0.65
Coal	0.55	14,000	Pounds	0.10
Electric	1.0	3,413	Kwh	0.085
Dist. Steam	0.7	1,000	Pounds	0.005
Air Ht.Pump	2.1	3,413	Kwh	0.085
Water Ht.Pump	2.8	3,413	Kwh	0.085

Tables I, II, and III are representative of the nature of the data that are provided as defaults to the building designs. There are several additional parameters that are defaulted, but these are too numerous to include in this paper. Some of these parameters are: winter and summer in-door design temperatures, building occupancy hours, hot water usage, cooling system type, heating fuel type, building's mass, and infiltration rate. All of these parameters are provided by system as default values according to the selected building type. Changes are possible for all the parameters at the desire of the designer while the building is undergoing its design examinations.

COMPUTER-AIDED PLAN GENERATION

One of the options provided in the software is the automatic generation of building plans based on space relationship criteria provided by the designer. An automated space planning algorithm is applied in the early design stage to help the designer define building layouts. This is done interactively by using the designer's space relationship criteria a predefined geometric knowledge base. With this tool, designers can easily create and modify building layouts and apply the results to test the energy performance during the building's early stages. This aspect is described in an earlier report by Huang and Degelman (1992). This feature is depicted in Fig. 1.

As an alternative, the designer can also generate a building layout by manual methods by sketching into a blank matrix on the screen. In this system, all the geometric information will be updated interactively and fed back to the designer automatically.

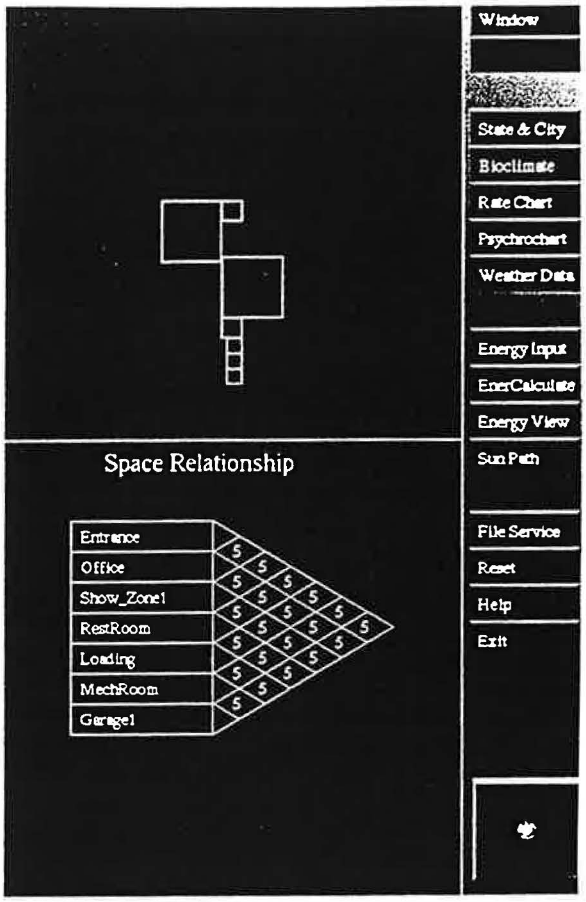

Fig. 1 Space allocation and generation

CLIMATE EVALUATIONS

Designing a building for energy efficiency means providing an indoor environment that most nearly approaches human comfort conditions with minimal investment in purchased energy. In architectural terms, this means that the building design should utilize natural climatic features to improve conditions with as little use of mechanical apparatus as possible. But how much benefit can be gained from the natural environment in a given location? What is the most significant climatic feature of given location? To find the answers, designers need to scrutinize the local climatic conditions. Most designers do not involve themselves in this sort of in-depth study, because a comprehensive set of local climatic data are often difficult to obtain, and when it is obtained, it contains thousands of numbers that are hard to understand (and certainly hard to visualize). Thus, an efficient graphical presentation plays an important role in helping designers understand the local climate. This program provides three common graphical representations: the Bioclimatic chart, the psychrometric chart, and a weather summary bar chart (see Fig. 2). The weather summary chart is a plot of monthly min/max dry-bulb temperatures as well as degree days, so there are two different scales.

The heating degree days begin at the top edge and are plotted downward, while the cooling degree days begin at the bottom edge and are plotted upward. The temperatures are plotted in the center portion. All of these have the human thermal comfort zone superimposed. Any city, from a data base of 257 U.S. cities plus 14 other international sites, may be selected and displayed within seconds.

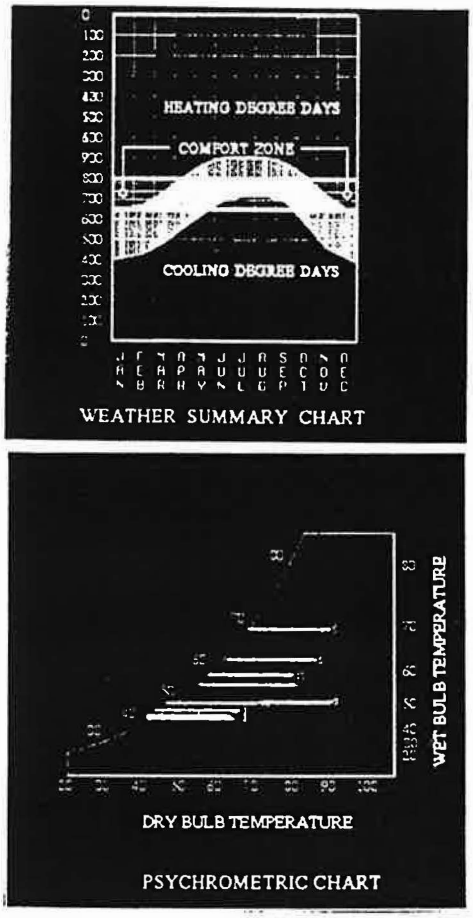

Fig. 2 Weather data display screen options

The weather data selection is an automatic process and is done by first specifying the name of a State. The program instantly displays the available weather stations in that State, and the user simply selects one of the sites by city name. Each of the 257 U.S. cities in the database contains the following weather statistics:

- City name, latitude, longitude, local time meridian, and elevation above sea level,
- Monthly average dry-bulb temperatures,
- Standard deviations for same,
- Monthly average maximum dry-bulb temps,
- Standard deviations for same,
- Monthly average dewpoint temperatures,
- Standard deviations for same,
- Monthly average daily horizontal insolation, and
- Monthly average wind speeds.

The designer has the option of displaying a table of the above values in addition to the graphical depictions shown in Fig. 2. The amount of energy a building will require to perform its heating and cooling functions will depend on its average balance temperature. As an example, this balance temperature for the heating season is:

$$TB=TS - (HGS+HGI)/(\Sigma UA+1.08*cfm) \qquad (1)$$

where,

TB=balance temperature
TS=interior setpoint temperature
HGS=heat gain due to solar
HGI=heat gain from interior lights and people
ΣUA=sum of UA coefficients
cfm=cu. ft. per min. of outside air

After a thermal balance temperature has been found for the building, degree-hours need to be known above or below that balance temperature. Using the statistical weather data summaries, it is possible to compute heating and cooling degree-hours at any base temperature. It is also possible to estimate the outdoor design temperatures without having the user look to other design temperature references. A 95% to 97% summer design condition is fairly close to 2.1 standard deviations above the mean daily maximum temperatures in the hottest month. The winter design temperature is the counterpart for the coldest month.

Annualized heating loads then can be estimated by multiplying the ΣUA value (Btus per degree-hour) by the number of heating degree-hours below the balance temperature. The balance temperature therefore becomes of design interest because it is affected by the amount of solar energy that is admitted into the building in the winter. The designer will see the energy consumption increasing or decreasing as window areas are changed on the building or glass shading coefficients are changed.

A similar technique is used for the cooling season, except it adds internal heat from lights and the latent loads from outside air. To handle this, the computer model calculates not only the cooling degree-hours (for conducted and sensible ventilation loads) but also the cooling ***hours***. Using a statistical technique, the number of hours that the outdoor conditions are above the balance temperature are computed (cooling hours). Then, constant loads from lights, people, and humidity are simply multiplied by the cooling hours that occur during the occupied periods.

Since balance temperatures are derived for an average condition, then the solar heat gains must also be for an average day. In deriving the average insolation on the building's walls and roof, a simple technique is employed. The technique for doing this is described in the next section.

SOLAR IMPACT ANIMATION

Any building design should be in harmony or have a complementary relationships with its natural surroundings. It is the designer's role to determine the physical limits of this specification by constructing an envelope that can obtain the suitable amount of impact from the physical natural environment. The amount of this impact is derived directly from the size and shape and orientation of the building. This means that the envelope also must properly respond to the diurnal and annual rhythm of the sun. This system can simulate the hourly thermal impact and can thus assist the designer in attempts to limit the need for mechanical cooling/ heating.

The system contains four different viewports (3D view, plan view, South view and East view) that can help the designer visualize and understand the relationship between sun movement and the building's location, shape and orientation. Designers can choose any date within a year, then the program will automatically animate the sun motion in steps of 15 minutes, half-hour, or hourly throughout that date. (See Fig. 3). Also, the program will create animation of the building shadows which accurately depict the relationship between the building shape, orientation and current sun position.

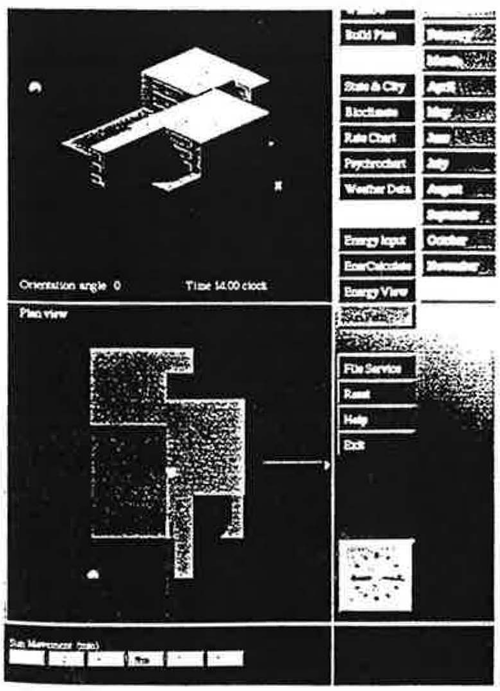

Fig. 3 Solar impact and shadow simulation.

Besides drawing the building shadow, this system also can depict the solar gain on a given building by using an color mixing technique. When the designer selects the preferred location and date, the program will automatically calculate the clear-day hourly solar gain on each wall and display the solar gain with prescribed colors. This is a simplified process that utilizes default clear-day coefficients from Table 1 of Chapter 27 in ASHRAE's ***Handbook of Fundamentals (1989)***, (See Table IV.)

Incident solar radiation is calculated hourly on each of the building's exposed walls for a clear day. The formula for this calculation is derived from methods published by ASHRAE (1989). The equation for clear-day hourly insolation on each exposure begins with Eq. 2:

$$IDN=ASC*\exp(-AEC/\sin\beta) \quad (2)$$

where, IDN=Direct normal insolation
ASC=Apparent solar constant
AEC=Atmopheric extinction coefficient
β=Sun altitude angle

The values for ASC and AEC are obtained from Table IV. The value for β is obtained from earth-sun relationship equations that are published elsewhere (ASHRAE 1989; Degelman 1991.)

One use of the solar radiation calculations is to establish the building's balance temperature, as described in a previous section. To do this, data from Table IV and the weather database are employed. First, the clear day solar values are computed based on Eq. 2 described above and the values from Table IV. Secondly, the actual horizontal insolation (read from the weather database) is divided by the computed extraterrestrial horizontal insolation.

Table IV. Monthly solar constants and atmospheric extinction coefficients. (ASHRAE 1989)

Month	AEC*	ESC*	ASC*
Jan	0.142	448.8	390.
Feb	0.144	444.2	385.
Mar	0.156	437.7	376.
Apr	0.180	429.9	360.
May	0.196	423.6	350.
Jun	0.205	420.2	345.
Jul	0.207	420.3	344.
Aug	0.201	424.1	351.
Sep	0.177	430.7	365.
Oct	0.16	437.3	378.
Nov	0.149	445.3	387.
Dec	0.142	449.1	391.

* Table symbol key:
AEC=atmospheric extinction coefficient.
ESC=Extraterrestrial solar const. (Btuh/sq.ft.)
ASC=Apparent solar constant (Btuh/sq.ft.)

The clearness index, is an exact measure of the average fraction of solar radiation reaching the building site. From this clearness index, the percent sunshine value can be derived. Then, the average insolation may be estimated to be the percent sunshine value times the clear-day insolation values. This is actually the value used in the balance temperature equation. (Eq. 1)

Solar impact visualization.

As the solar heat gains are computed, the thermal impacts are displayed in color. According to the color theory, each color has three basic components -- R,G,B (red, green and blue). By using spectrum theory, different colors have different thermal units. Conversely, different thermal values can be represented by different colors. Thus, the hourly solar gain of each wall can be viewed within the animation by displaying different colors according to its thermal value (see Fig. 3). Moreover, this system can also present the hourly impact of building shadows on the solar gain. With this feature, it is very useful in helping designers to understand the energy ramifications of sun movement, building shape, and orientation, and can result in an improved thermal design for the building.

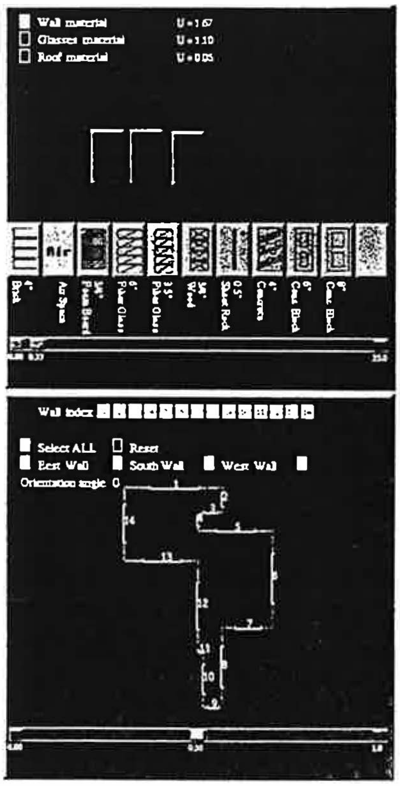

Fig.4 Envelope selections with material icons

WALL AND WINDOW MATERIALS

Typically, describing building materials is one of the most tedious jobs during the energy design stage. By using a GUI (Graphical User Interface) to edit building materials, this task has been minimized. To allow the designer to edit building materials, this system displays both an image of the wall, roof, or window assembly and the building layout to show where the material is located. Designers can describe wall, glass, and roof materials either by selecting a single wall or multiple walls at one time. In this stage, designers can freely assemble the selected material icons in any order and form the desired wall sections (see Fig. 4). Once the designer selects the building material icons, the program will print out the default R-values of the layers and the total U-value of entire assembly. All the editing control is by using the mouse to select desired walls, material icons, or change R-values with the scroll bars. All user input data are stored in the data base. Through this GUI system, designers can integrate the building layout and describe their energy design parameters in less time and do it more accurately.

RESULTS FEEDBACK ADVISER

Energy analysis results data are overwhelming when presented in numerical format. Thus, a graphical feedback model is provided to aid designers in improving the chances for energy efficient designs. Graphical feedback of energy results is provided via bar charts, 3D surface plots, and animation of the sun motion showing real-time impacts on the building's thermal loads.

Animations include both shadowing and insolation intensity distributions. These are created by applying spectral theory to convert temperatures to specific colors and then plot both in the 3D view or plan view. The building plan is divided into square cells. Temperature in each cell is computed according to thermal conditions at its boundary, and the cell is colored accordingly. While this is happening, the system updates the annual energy performance as well -- thus, revealing the altered inputs dynamically. Thus, designers can understand how energy performance is affected by the building shape, envelope materials, orientation, location, etc.

The primary purpose of this computer model is to calculate the annual energy performance and communicate this quickly to the designer. The software estimates the annual energy performance of using a simplified energy analysis method known as the variable-base degree-hour method. The tables of values included in the output permit the user to quantify the energy consumption and the potential savings in fuel and electricity for a building. Bar charts allow the designer to visualize the relative sizes of the energy consuming components with respect to each other. This is intended to focus the designer's attention on the most important areas of potential benefit for reducing energy consumption.

Energy adviser.

A target value of energy consumption (in Btus per sq. ft. per year) is constantly displayed as a horizontal bar. Coincident with this value, and at the same scale is a vertical bar showing the performance of the building under study. The relative position of the performance bar and the target value tells the designer whether further efforts in energy saving strategies are recommended. If the target energy value is exceeded, then the designer's attention is directed to the component energy use bar chart. This reveals where the problems are. In addition to the visual displays, the program also generates "energy advice" statements telling which strategies have the highest potential for saving energy. These statements currently are based on the same observations that the designer could derive from the bar charts, but they are provided as a backup checklist. (See Fig. 5.)

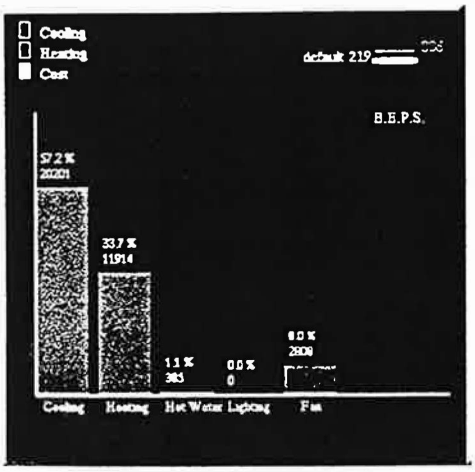

Fig. 5 Graphical feedback of energy performance

CONCLUSIONS

As a tool for the design of environmentally responsive buildings, ENERGRAPH can be used both early and late in the project. At the very beginning of the process, the designers can gain an overall picture of the project's energy design assets and liabilities, or can rapidly test alternative design ideas, such as different building materials. Toward the end of the design process, ENERGRAPH can used in terms of the relative contribution of each of the many components. The final objective is to produce a humanly comfortable environment with the less aid of mechanical conditioning.

ACKNOWLEDGMENTS

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