DOE/RL/11746 - T2

DOE/RL/11746--T2

DE91 018940

# LIQUID-CRYSTAL FILLED, HOLOGRAPHIC SOLAR CONCENTRATOR

Advanced Environmental Research Group, Inc.

Grant #DE-SG06-89RL ~~11671~~ 11746

INNOVATIVE RETROFIT CONCEPTS
FOR SAVING ENERGY
IN EXISTING BUILDINGS

AUGUST 20 1989

Prepared by AERG
for the Department of Energy
Richland Operations Office

(signed)

Hendrik Gerritsen, Principal Investigator

Richard Ian-Frese, Project Director

**Abstract:** The concept to be examined for feasibility involves the use of holographic diffractive structures (HDSs) to collect and redirect sunlight from the whole range of solar angles as they vary with the hour of the day and the seasons of the year. These HDS collectors can be used on any building surface to project sunlight into interior spaces which have no direct access to natural light. Spaces such as plenums which exist for the accomodation of HVAC equipment or air shafts could serve as hollow light guides through which the sunlight is projected. The sunlight will be reflected by baffles at the receiving end to serve as a useful source of illumination which can replace electric light whenever the sun is shining. Substituting sunlight for electric light will save energy for both lighting and cooling, particularly during summer peak-loading conditions, while at the same time improving the quality of illumination within the space. It is anticipated that the HDSs will provide a rellatively inexpensive alternative to mechanical sun-tracking devices.

## Introduction and Background

**Advanced Environmental Research Group (AERG)** is a partnership with expertise in holographic research, architecture, optical physics and engineering with affiliations at Harvard, MIT and Brown University. Since its incorporation, AERG has gained international status in its field The majority of the research work has been funded by the U.S. Department of Energy In addition to its DOE contract and grant awards, AERG has won awards for energy innovation from Boston Edison (Centennial Invention Competition), the 1986 Energy Innovation Award in Massachusetts and the New York chapter of the Illuminating Engineering Society, which recognized AERG with a specially created "Award of Excellence" for innovative work in the field of lighting research.

AERG has also published in a number of scientific and technical journals and has been the subject of a number of magazines and newspapers articles in such publications as the Wall Street Journal, Discover Magazine, Architecture, and High Technology magazine AERG has presented papers before technical organizations internationally, exploring potential areas of collaboration and new applications.

Although the field of holography is no longer very new, there are still many areas within it which are not well understood. AERG, in attempting to design holographic diffractive structures (HDSs) for daylighting applications, has been led into doing original research in some of those areas. The product characteristics demanded by the marketplace present technologically demanding problems requiring innovative and sophisticated solutions.

These solutions require not only a fundamental understanding of the physical principles underlying holography, but also the skills and expertise to advance that understanding and integrate it into the world of architecture. Under the sponsorship of the U.S. DOE Solar Buildings Technology Program since 1985, AERG has been exploring a window system incorporating holographic glazing.

Although awareness of the value of daylight in buildings is not new, the use of direct beam sunlight has been limited by the difficulty of controlling heat and glare and the damage to interior furnishings from ultraviolet radiation. During the last four years of research at Brown University,AERG has proved the theoretical feasibility of using holographic diffractive structures (HDSs) in a window to redirect sunlight away from the floor into more useful locations. Sunlight which strikes the window surface is redirected into a diffuse wash of light across the ceiling, creating much the same effect as a skylight, but with the full sunlight spectrum.. Replacing electric light with sunlight in this way saves both on lighting and cooling costs in office buildings while enhancing the quality of the lighting in these spaces..

Prototype HDSs have been completed which demonstrate the capabilities of the material. Real-sky evaluation at the Harvard Graduate School of Design, verified by the DOE at Lawrence Berkeley Laboratory, showed an increase in light levels of between 150% and 200% at a distance of 27.5' from the window wall of the test model, with a significant reduction in glare.A four foot band of the product across the top of the window is capable of providing continuous ambient lighting thirty feet deep into the room.

The glazing material under development incorporates the HDSs in a thin embossed plastic film which is appled to or incorporated into a window. The HDS material is produced by making a photoresist "master" which is processed by laser light to produce a specific and carefully designed pattern of microscopic ridges and valleys. This photoresist "master" is then metallized to make it hard enough to be pressed into a thermoplastic film in the mass-production embossing process. AERG is now working on translating the photoresist HDSs into the production technology

The window film form of the product is also a significant advantage over competing daylighting products, as it will require less compromise in building design The product will provide a significantly improved lighting environment for the occupants of the holographically sunlit rooms. The use of natural sunlight instead of fluorescent lighting can be expected to improve worker morale and productivity.

In this present investigation, AERG turns its attention to a concept which will permit the introduction of sunlight into windowless spaces in the interior of buildings, and to the utilization of blank south-facing walls and roof areas for the purpose of introducing sunlight deep into building interiors. The device being investigated will also lend itself to controlling glare problems as, for example, from west-facing windows or from troublesome reflections off of adjacent buildings.

### Description of the Concept

The new concept under investigation in this study looks at the feasibility of using these HDS structures compounded in series as a holographic concentrator. The application to existing buildings will be in using areas of the building surface other than windows to admit sunlight and project it into interior spaces which otherwise would have no access to natural light. These HDS collectors could be mounted on the spandrel spaces between floors, and utilize the spaces between HVAC feeders as hollow light guides to conduct light deep within the building. The light would be reflected downward by an inclined ceiling surface above the area where the illumination is desired. Any blank wall space which receives sunlight could project sunlight into the building interior.

Another possibility lies in converting existing air shafts into light wells by using the HDS concentrators to gather light from a wide range of solar angles and projecting it downwards, perhaps through some controlled reflections off interior surfaces, creating the same lighting effect as would be achieved by a much larger atrium.

The compounded HDS glazing material will consist of three different HDS designs layered over one another. Each layer will be tuned to a particular range of incoming sun angles covering approximately 60 degrees of solar altitude and azimuth. Each grating will come into play at the appropriate sun angle through the action of a liquid crystal material which fills the spaces between the layers of HDSs. The index of refraction of this intervening material will be altered by the application of a tiny voltage which will have the effect of causing the inappropriate HDSs to optically "disappear" so that the HDS appropriate for that range of sun angles can operate without optical interference by the other HDS layers.

The tiny voltage which produces this switching action can supplied by a small solar cell which is physically oriented in a direction which causes it to trigger when the sun reaches a certain point in its trajectory across the sky. This arrangement would obviate the need for complicated wiring and controls.

## Economics and Marketing

The efficiency with which sunlight can be used is limited by conversion factors and transmission losses. The Department of Energy has come up with dollar values for one square foot of sunlight flux over the course of one year, utilized in various ways..The dollar value of sunlight can be expressed as follows:

thermal energy 300,000/BTU / $ft^2$/year, worth **$1.80** @ $6

electrical energy 80 KWH / $ft^2$/year, worth **$6.40** @ $.08

directly as light...8x $10^6$ lumen-hours/ $ft^2$/year

--worth $26.00 @ $3.30/$10^6$ lumen-hours

Q.E.D.: By far the most effective way to use sunlight in conserving energy is by using it directly as light to illuminate the interiors of buildings.

Limitations of Existing Technologies:

The introduction of sunlight into windowless interior spaces has been hitherto accomplished by various ingenious combinations of mechanically tracking mirror arrangements and fresnel and/or prismatic lens transfer systems or fiber optics. These systems can be highly efficient, but they have certain drawbacks. Any mechanical tracking system, no matter how well designed and maintained, is subject to Murphy's Law. Mirrors collect dust very quickly and so require cleaning in order to maintain their reflective efficiency. The same is true of lenses, which also produce chromatic aberration, and are optimally effective over a relatively narrow range of incoming sun angles. All of these systems are very expensive, and for this reason will not be so widely used as to have a large effect on energy savings

Light pipe and fiber optic systems can convey and distribute light throughout a building, and especially to the core area while filtering out the undesirable infrared and ultraviolet. However these systems also have inherent limitations in the levels of absorption and reflective losses within the material, as well as the requirement for a large, expensive mechanical tracking system to accomplish the task of concentrating sunlight into the guide. This tracking-delivery requirement could be addressed more elegantly by the use of advanced holographic diffractive structures which are lightweight, durable, compact, and comparatively inexpensive, and require no more maintenance than an ordinary window.

The HDS maintains another important advantage over these technologies, as it will require less compromise in building appearance and design. Competing daylighting techniques often obstruct views or require a building to be designed around their use. HDSs can potentially serve well in both the capacity of a "stand-alone" device or in a complementary manner to optimize the effectiveness of other light-delivery systems.

Target Markets:

AERG will promote the concept primarily on the basis of its energy savings potential. Lighting and associated cooling loads represent 30-80% of energy costs in office buildings depending upon building size, type, location, use and orientation. Since lighting is such a large component of the energy budget of a building, commercial retrofit budgets usually include a major lighting overhaul, and holographic lighting could be designed into such a project.

There is also a possibly significant market to homeowners, school, hospitals, etc, which would be based on the aesthetic improvement of the lighting environment. Other potential specialty institutional markets include museums, libraries and educational facilities. These institutions place a higher value on operating costs and aesthetic considerations. Speculative buildings by developers are likely to be late adopters of the concept. They emphasize capital costs rather than operating cost, and lighting systems are often a prime candidate for cost cutting.

Once a product is proven to save energy, however, the developer is likely to use it as a way to differentiate his or her building. One can cite the example of low-e glazings which are now a touchstone of quality construction, although the low-e windows look exactly like ordinary windows to all but the practiced eye.. The HDS installations, by contrast, will be visible in themselves and also make a very visible difference.in the lighting quality within the space.

Peak Loading Considerations:

A significant aspect of the concept of holographic sunlighting is that hours of peak sunlight availability often, though not always, coincide with peak electrical loading conditions e.g. on hot summer afternoons when the already large cooling loads are increased by waste heat from the electrical lighting fixtures. These peak-loading watts are expensive for the utilities, as they have to be supplied by reserve capacity which is usually obsolete and inefficient, or by building new capacity, with all the economic risks which that entails

For this reason, building managers pay a large penalty for allowing their electrical use to impinge on these peak-loading conditions. If, by avoiding the use of electric lighting during sunny afternoons, the HDS material fulfils its promise in reliably controlling peak electrical loads, there may be an up-front capital saving realized by downsizing the required (and very expensive) cooling plant capacity.

Implications for the Working Environment:

Decision makers in the building sector recognize that energy savings are only part of the picture. By far the largest element in the overall life-cycle cost of a building is the cost of the people who will work there. The first cost of constructing and furnishing a building is only about 2% of its lifetime cost. Employee salaries and benefits are the truly significant long-term expense. It is of prime economic importance to create an environment which will help attract and keep productive employees. Too many energy-saving lighting strategies have a negative effect on the lighting environment within the space. Any decision which adversely affects the comfort and health of occupants is likely to prove very expensive in terms of lost productivity.

It is important to emphasize, therefore, that the full-spectrum illumination which the diffracted sunlight offers is radically different from the limited spectra of artificial lamps, and there seems to be good reason to expect that there will be benefits in both comfort and health to occupants from the use of natural sunlight for illumination, for even a part of the day. This same full-spectrum quality should make the material useful in homes, schools, and hospitals, where lighting costs are not a dominant consideration.

Possible Other Applications for the Concept:

The capability for redirecting sunlight from a wide range of incoming solar angles into a controlled location has many other potential applications. Wherever there is a need to bring more solar energy into a limited aperture, the HDS structures can find an application. If the liquid crystal filled, stacked HDS concentrators fulfil the promise of the concept, they may to some extent replace mechanical tracking arrays of mirrors for solar thermal applications.

The HDSs might serve as a concentrating cover for a solar pond (reducing evaporative losses at the same time). They might make it possible to bring in the same amount of light through reduced glazing areas for greenhouses and other growing structures. The resulting control of unwanted heat losses and gains may make it possible to grow crops under cover in harsher climates than ever before.

If the HDS material can reduce the cost of concentrating solar energy sufficiently, it could be used in solar stills to make fresh water from sea water, or to drive any number of chemical processes, possibly including the production of Hydrogen fuel.

There is no reason why the HDS material cannot be used to control the distribution of light from artificial sources as well, for example, we have been approached by people from NASA who are doing a habitability study for the Space Capsule in which they want to control the distribution of light within the space very carefully, avoiding any strong contrasts in surface brightness. The HDS material could probably be engineered into a very lightweight, compact luminaire which would do this job. A similar luminaire might be equally useful in more ordinary buildings, spreading light more evenly, reducing glare, and probably even the required number of fixtures and even of watts/square foot.

The double-axis tracking capability of the HDSs could be useful in photovoltaic applications. HDSs in a vaulted configuration could also be used as a load-matching device for photovoltaic arrays, intercepting maximum solar flux at the times of day when demand is greatest (and conversely shifting the scattering losses to the times of day when demand is less) . The capability of the HDSs to control the direction in which the colors of light are dispersed could be utilized to distribute the sunlight spectrum in the appropriate color to different photovoltaic materials, each receiving the bandwidth to which it is most sensitive. This could bypass the absorption losses which are inherent in stacked photovoltaic cells.

## Key Experimental Results

We have demonstrated two different effects obtainable with liquid crystals which promise to be useful for solar applications.

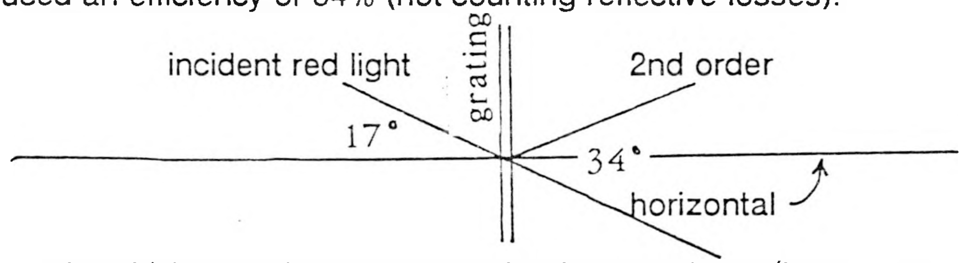
## The Variable Grating Mode (VGM) liquid crystal device

**The first device** is based on the Flexo-electric effect. It was discovered in1963 by Williams, and since then several people have done some work on it We have been in contact with, in particular, Hughes Richards Laboratories and the University of Southern California. They have exploited, for optical computer applications, the effect which is produced when you place liquid crystal in between two plain parallel plates with conductive coating, held apart by a spacer of a couple of microns in thickness, and then apply an electric field. Under these conditions a diffraction grating spontaneously appears, and the spacing in the diffraction grating is proportional to the voltage which is applied. Higher voltages give a finer grating.

. Our experimental plan has been to apply a voltage of such a value that the incident light is diffracted into a specific desired area with a high degree of control. The device which we are working with at the moment tracks over a range of up to 35 degrees between the incident angle and the diffracted angle, and requires 40 volts DC with a current of fraction of a a small fraction of a micro-ampere . We can use two gratings working in series. In one case the grating is horizontal and in the other case it is vertical. One grating will control altitude changes and the other will control azimuth changes.

**The best results so far** have been obtained with a 8um thin cell of liquid crystal material, which produced an efficiency of 84% (not counting reflective losses).*

for red light




With a somewhat thicker grating and somewhat larger voltage (but an extremely small current still) we expect to get large efficiencies for angles near 50 degrees.*

**The second device** which we have started to work with uses an existing diffraction grating made in plastic, which is then coated with a transparent conductor and filled with indium tin oxide, (ITO), a common transparent conductor. As in the case of the first device, an electric field was applied between the two conductive coatings. In this cas the electric field changes the lineup of the liquid crystals which fill the diffraction grating.

* *additional information may be obtained from the authors under an appropriate non-disclosure agreement*

When the electric field is off, the refractive indices of the liquid crystal and the grating are matched, and the effect is to make the grating optically disappear. When the electric field is applied the reorientation of the liquid crystals creates a difference in the refractive indices of the liquid crystal and the grating, and the grating becomes once more optically active. The switching speed of the device is a few tenths of a second after the voltage is changed before the new spacing is established, typically about .3 seconds.

This device has the advantage that the specific location of the diffracted light is well defined, and the optical clarity can be very good. The problem here is efficiency, because the difference in refractive index between the liquid crystal in its switched state and the plastic grating is not very great (typically, at best, about .2), so that the grating must be made fairly deep (about 1/5 width to depth ratio). In order to get high efficiency we need to learn how to make really deep diffraction gratings. We didnot expect to achieve high efficiencies within the scope of this study, but we havedemonstrated that the effect does work.

In all of the gratings used so far the conductive coating on the plastic coating was aluminum. As soon as an electric voltage was applied, the aluminum coating balled up into small globs, and the experiment thus failed except in the case of one grating in which the aluminum held out a bit longer and a change in diffraction efficiency was seen. New experiments are now underway with heavily coated plastic gratings used in the reflection mode. In the near future we will also try to sputter ITO onto the plastic gratings in order to be able to work in transmission

## Future Work

Another area which requires attention is the optical clarity of the device..When you get to rather high voltages, there is a limitation in the amount of voltage which you can apply, which is that at a certain point the impurities in the liquid crystal material begin to destroy the clarity.. This limitation in the permissible voltage consequently limits the spacing in the diffraction grating. If you have good clean liquid crystals, and can maintain that purity over time by sealing them well, they should maintain their optical clarity for a long time. In this case it will be possible to apply a high voltage, get a large diffraction angle and still get efficient gratings. There is a question also concerning the stability of the liquid crystals under long exposure to sunlight, and the kind of protection which they may require. We will want to do some work with the Chemistry Department on purification and stability of the liquid crystal materials.

In order to get a broader tracking angle we might be able to use a stack of these liquid crystals. If we want both tracking and very high efficiency in this mode, we would have to control both the voltage and the thickness of the liquid crystal layers, and at the moment this does not look very feasible. What we may be able to do is to use several layers of different crystals, all optically contacted so the layers are quite thin and there is no light loss. The layers would be switched in and out as the sun angle changes, with small light sensors aimed in precisely the right direction to switch on the appropriate layer for that sun angle. The voltage could be applied from a small PV cell,suitably stepped up, since the electricity is only needed when the sun is shining.

## References, (Liquid Crystal)

1) Dispersive Concentrating Systems Based on Transmission Phase Holograms for Solar Applications, W. H. Bloss, M.Griesinger and E. R. Reinhard, Appl. Optics 21, 3739 (1982)

2) Optics of Non-Imaging Concentrators, W. T. Welford and R. Winston, Academic Press, New York, (1978)

3) Dispersion Effects in Relief Holograms Immersed in Near Index-Matched Liquids, or Christansen Revisited, H J. Gerritsen, Appl. Optics 25, 2382 (1986)

4) Optical Properties of Thin Nematic Liquid Crystals Cells, Shin-Tson and Uri Efron, Appl. Physics Letters 48, 624 (1968)

5) Electrically-Controllable Domains in Nematic Liquid Crystals, W. Gruebel and U. Wolff, Appl. Physics Letters 19, 213 (1971)

6) Physical Characterization of the Variable Grating Mode Liquid Crystal Device , A. R. Tanguay, C. S. Wu, P Chavel, T. C. Straud, A. A. Sawchuk, B. M. Soffer, Optical Eng. 22 (1983)

## AERG Publications

"Natural Illumination and Lightwave Technology: Update '88," , R. Ian-Frese, E. King, Proc. 13th Passive Solar Conference, (ASES)Cambridge, Massachusetts, with E. King, (1988)

Lightwave Technology and Holographic Comfort Systems" , with R. Ian-Frese, E. King , Invited paper, Proc. of the International Symposium on Advanced Comfort Systems for the Work Environment, Center for Architectural research, Rensselaer Polytechnic Institute, Troy, NY, (1988),

"Future Glazings and Lightwave Technology", R. Ian-Frese, Proceedings of the ISES Solar World Congress in Hamburg, West Germany, Pergamon Press(1988)

"Holography, Architecture, Intention" E. King , S. Weber, SPIE, Proceedings of LASE '87, Los Angeles, California (1987)

"Holographic Glazing Materials for Managing Sunlight in Buildings", R. Ian, E. King, The Journal of Architectural and Planning Research, University of Texas at Arlington, Arlington, Texas, (1986)

"Holographic Diffractive Structures: Future Glazings Through Lightwave technology", R. Ian, H. Gerritsen, E. King, D. Thornton, and S. Weber) Annual Report FY86/87 USDoE.(1987)

"Holographic Solar Access" ,R. Ian, S Weber and E. King, International Solar Energy Society, Proceedings I of the Second International Daylighting Conference, Long Beach, California (1986)

"Holographic Aquaculture System" R. Ian, E. King, Optical Society of China, Conference Digest of the International Conference on Holographic Applications (ICHA '86), Volume 673, Beijing, China (1986)

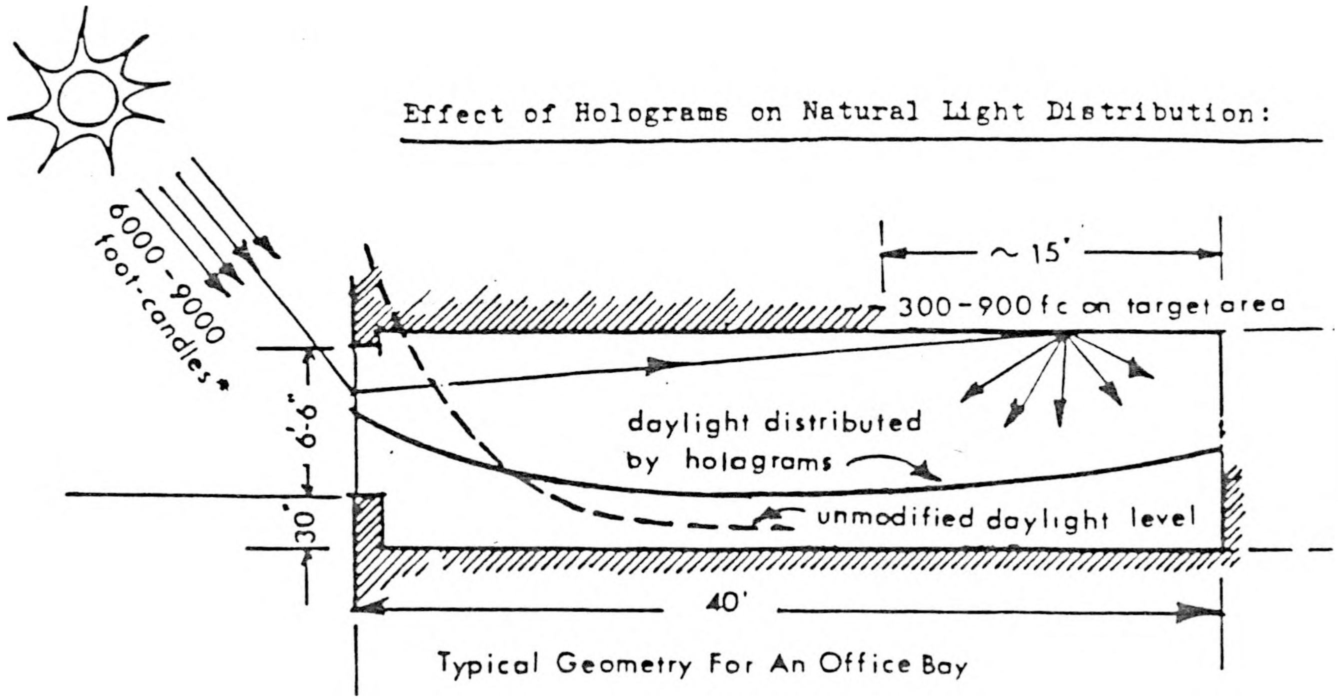
"Holographic Aquaculture" R. Ian, E. King, invited paper, American Solar Energy Society, Proceedings of the 11th National Passive Solar Conference, Boulder, Colorado (1986)

"Holographic Diffractive Structures for Daylighting: Direct Illumination" R. Ian, E. King, American Solar Energy Society, Proceedings of the 10th National Passive Solar Conference, Volume 10, , Raleigh, North Carolina (1985)

"Holographic Diffractive Structures for Daylighting" R. Ian, H.Gerritsen, E. King, D. Thornton, and S. Weber, Final Report-Phase I FY85, U.S. Department of Energy, #DE-AC03-84SF15292

ADVANCED ENVIRONMENTAL RESEARCH GROUP
( D.#1, Box #1830, Woolwich, ME 0( '9
(207) 443-6587

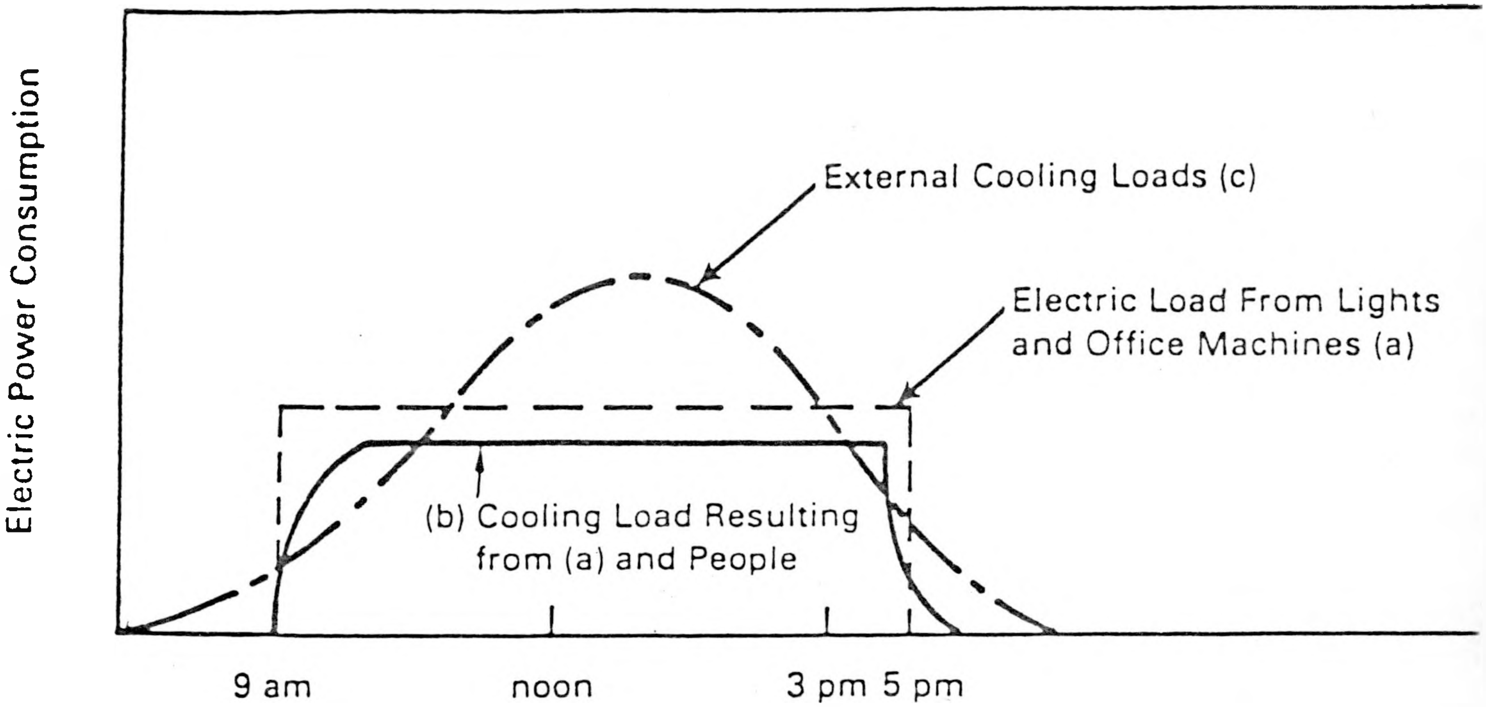
holographic diffractive structure (HDS) technology for practical sunlight illumination



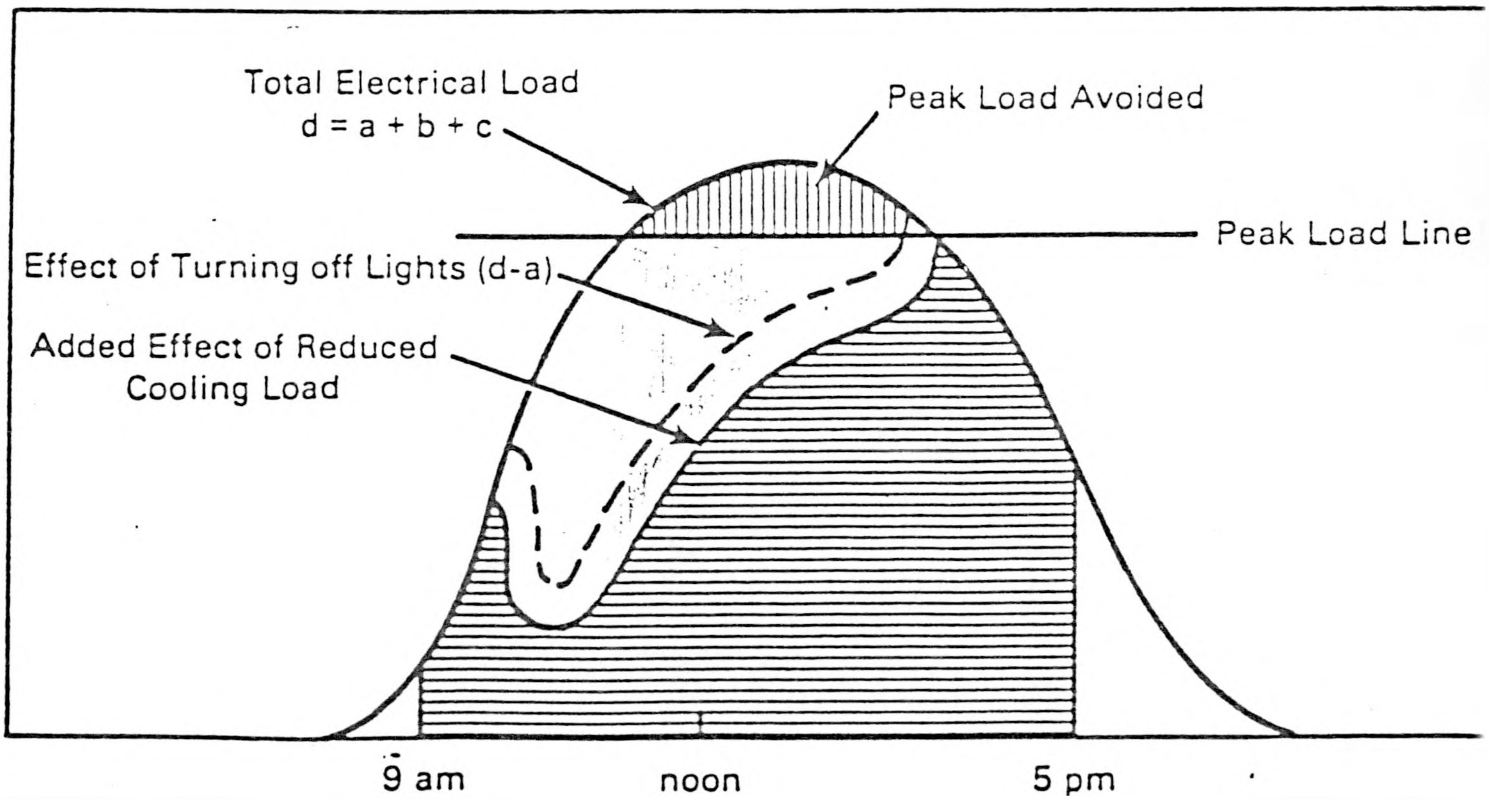

The HDSs are designed to redirect much of the extremely intense direct beam sunlight away from the area immediately adjacent to the window. The redirected sunlight is projected onto the ceiling and the upper part of the wall at the back of the room. This creates a balanced lighting environment approximating that of a room with skylights and windows on the back wall. . At the same time, the HDSs, by redirecting the sunlight away from the front of the room produce a shading effect on this otherwise uncomfortably bright region. All this is done without excluding any of the available direct or diffuse solar radiation.

The effect of the HDSs on the illumination within the room is to shade the area near the window from direct beam sunlight while allowing the diffuse sky illumination to pass through. The sunlight which strikes the surface of the HDS is transmitted with an altered direction deeper into the architectural space so that it plays over the surface of the ceiling near the back of the room and/or over the upper part of the rear wall.

(A) Components of electrical load in a typical office building

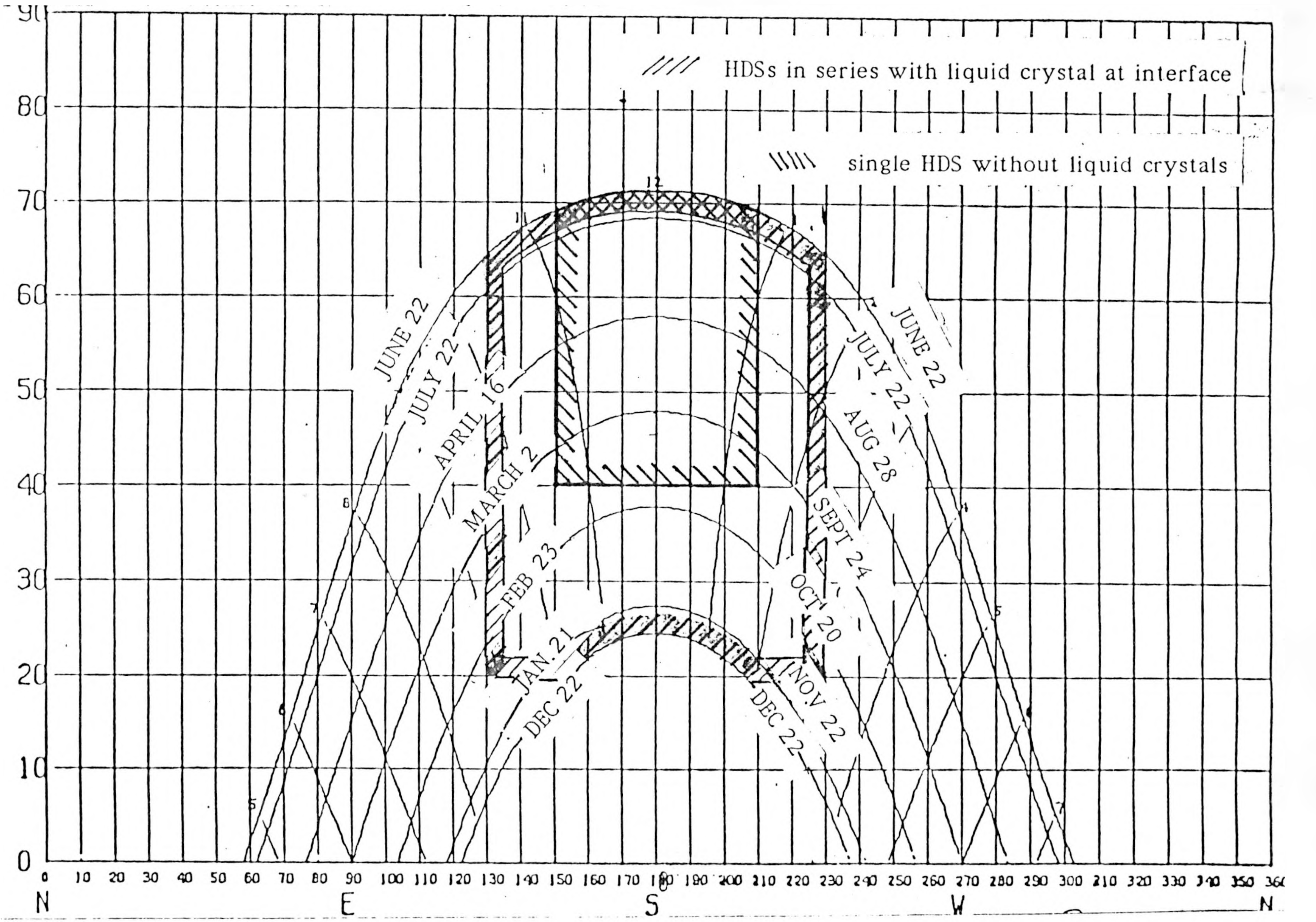



(B) Reduction of electrical loads as a result of daylighting
(peak loads tend to coincide with periods of
maximum available sunlight)




RELATION OF DAYLIGHTING AVAILABILITY TO PERIODS OF PEAK LOADING

SUNPATH FOR LATITUDE 42 DEGREES (from Ed Mazria's Passive Solar Handbook)




portion of the "sunpath" which can be passively "tracked" by the liquid-crystal filled holographic diffractive elements (theoretically).

ADVANCED ENVIRONMENTAL RESEARCH GROUP, INC