

# New techniques for reflector design and photometry

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Initiated by a project to develop floodlights for underwater applications, this paper explores the computer-aided creation of complex reflecting patterns by the individual design of perhaps hundreds of reflector subelements whose composite reflected light rays form the required distribution. The use of a continuous reflector profile was prohibited by the complexity of the required pattern, lamp type, and size constraints.

## Introduction

Reflector design has always been a fundamental part of illuminating engineering, and with the advent of high speed data processing, new possibilities are open for sophisticated designs. The particular project to be described involves the development of floodlights for underwater applications, using optical systems free-flooded with seawater. The methods described, however, are applicable to a wide range of reflector design problems and thus a general description of principles is included. Further background information is available through the References.<sup>1,2</sup>

## Design considerations

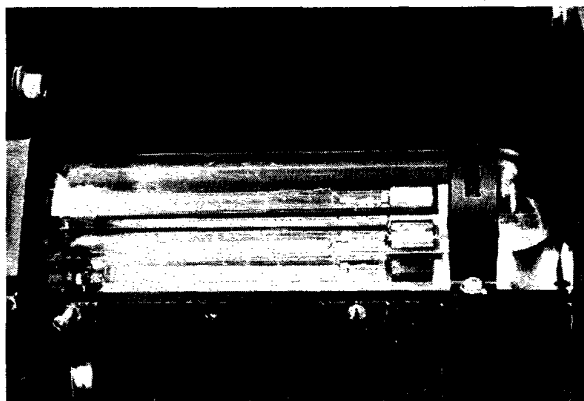
Four underwater luminaires for oceanographic purposes were developed, each with a different set of design criteria. The essential differences are basically the lamp type and the required luminous intensity (candlepower) distribution. The four lamp types are: (1) short arc metal halide; (2) quartz-iodine; (3) low energy xenon strobe; and (4) high energy xenon strobe.

As an example of lamp type, Fig. 1 shows the high energy strobe lamp, which consists of four straight 3.4-inch parallel xenon filled tubes. This causes a substantial complication in design work as not only do the rays from multiple sources need to be taken into account, but also the shadowing of one source by the other must be considered. Further, shadowing of the source by support rods and other mechanical features must be included in the design system.

Table I shows an example of one of the required luminous intensity (candlepower) distributions, in terms of a candela grid (values are relative). In general, all four patterns have the requirement of low values at the pattern center with a slow rise and then a rapid rise towards the pattern edges. Moreover, a sharp cutoff is required along the top of the pattern, with specified limits on the intensity that can be emitted above that line.

The complex pattern requirements result from the need to evenly illuminate the film in a camera situated in a fixed position with regard to the floodlight, or to produce even luminance on a television receiver, depending upon the particular luminaire. The pat-

Figure 1. Photograph of high energy strobe lamp, liquid-filled with four xenon flashtubes.



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**Table I—Example of required light distribution—values in relative light intensity (candelas)**

ALPHA ANGLE (VERTICAL)	PATTERN BOUNDARY															
	2.60	2.87	3.29	3.69	3.94	4.02	4.08	4.28	4.79	5.38	6.09	7.61	11.49	23.94		
21.25	2.60	2.87	3.29	3.69	3.94	4.02	4.08	4.28	4.79	5.38	6.09	7.61	11.49	23.94		
18.75	1.90	2.11	2.43	2.76	2.97	3.06	3.11	3.24	3.57	4.05	4.63	5.65	9.06	20.68	54.13	
16.25	1.48	1.65	1.92	2.19	2.39	2.49	2.53	2.63	2.87	3.25	3.73	4.46	6.42	12.84	31.56	
13.75	1.25	1.39	1.63	1.88	2.06	2.16	2.21	2.29	2.47	3.79	3.21	3.76	4.94	8.59	19.39	
11.25	1.13	1.26	1.48	1.71	1.89	1.99	2.04	2.11	2.26	2.54	2.91	3.30	4.17	8.48	13.40	31.68
8.75	1.08	1.20	1.39	1.61	1.78	1.89	1.94	2.01	2.14	2.38	2.71	3.10	3.74	5.46	10.53	24.08
6.25	1.06	1.16	1.34	1.54	1.70	1.81	1.87	1.94	2.06	2.27	2.59	2.90	3.46	4.85	8.90	19.64
3.75	1.04	1.14	1.30	1.48	1.64	1.75	1.81	1.88	1.98	2.16	2.42	2.73	3.21	4.35	7.53	15.89
1.25	1.02	1.11	1.26	1.43	1.98	1.69	1.76	1.82	1.91	2.07	2.29	2.58	2.99	3.84	6.13	12.11
0	-----															
-1.25	1.01	1.09	1.23	1.39	1.53	1.64	1.71	1.77	1.89	1.99	2.20	2.46	2.79	3.37	4.81	8.60
-3.75	1.00	1.08	1.21	1.37	1.51	1.62	1.69	1.74	1.82	1.95	2.14	2.39	2.67	3.03	3.83	5.98
-6.25	1.01	1.08	1.21	1.37	1.51	1.62	1.69	1.74	1.81	1.94	2.13	2.38	2.63	2.88	3.35	4.68
-8.75	1.03	1.11	1.24	1.40	1.54	1.64	1.71	1.76	1.84	1.96	2.16	2.41	2.67	2.92	3.38	4.68
-11.25	1.08	1.15	1.29	1.44	1.58	1.69	1.76	1.81	1.88	2.02	2.22	2.48	2.76	3.09	3.73	5.50
-13.75	1.14	1.22	1.35	1.50	1.65	1.75	1.82	1.87	1.95	2.08	2.29	2.59	2.85	3.25	4.10	6.31
-16.25	1.22	1.30	1.43	1.58	1.73	1.83	1.90	1.99	2.03	2.16	2.36	2.61	2.92	3.33	4.18	6.37
-18.75	1.33	1.40	1.54	1.70	1.84	1.95	2.02	2.07	2.13	2.24	2.43	2.67	2.94	3.27	3.90	5.55
-21.25	1.46	1.55	1.71	1.89	2.05	2.16	2.22	2.25	2.29	2.38	2.54	2.76	3.00	3.26	3.75	5.17
	1.25	3.75	6.25	8.75	11.25	13.75	16.25	18.75	21.25	23.75	26.25	28.75	31.25	33.75	36.25	38.75

terns therefore take into account the sharp reduction in illumination in a camera optical system as the edge of the frame is approached. A further important consideration built into the design requirements is the scattering effect produced by suspended particles in the water; their influence was determined by computer. Thus their effects were built into the distribution requirements in such a way that light scatter problems would be minimized.

To complicate the design problem further, an extremely limited space was made available for the reflectors. The available space was a small fraction of the volume a designer would wish to have available for floodlight reflectors, amounting to an average of an eight-inch by six-inch by six-inch space for each lamp and its reflector.

**Design method**

Typical methods of reflector design call for the assigning of a continuous surface around the lamp, the surface being a generally smooth contour shaped to produce the required distribution of light. The design is performed on the basis of computing reflected lumens from the surface as if it consisted of a multitude of extremely small flat elements that approximate the curved surface.<sup>3,4</sup> The luminous

intensity directed to an element must be known from measured data, and the solid angle projected by the element is calculated. Luminous intensity multiplied by the solid angle gives the incident flux upon the element, which when multiplied by the reflectance gives the reflected flux. The reflected flux values can be used to determine the resultant luminous intensity distribution from the reflector as a whole by summing the contribution from the individual elements, assumed to be joined as a continuous surface.

The complexity of the required pattern, efficiency, lamp type, and size constraints were such that in fact it was impossible to use any form of continuous reflector profile. If it were required that each design element of the reflector had to join smoothly to its adjacent elements, then it would be necessary to accept a serious deterioration in the efficiency or in the pattern able to be produced. A different approach therefore was used.

As described above, the reflector area is considered to be formed of discrete elements for the purpose of the flux computation. In this reflector design, however, the elements are physically discrete, that is, one element is not necessarily joined to its neighbor. The reflector therefore consists of a large group of indi-

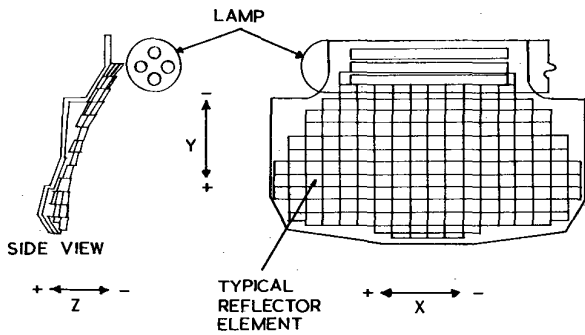


Figure 2. Views of half a reflector system, showing x, y, z coordinates.

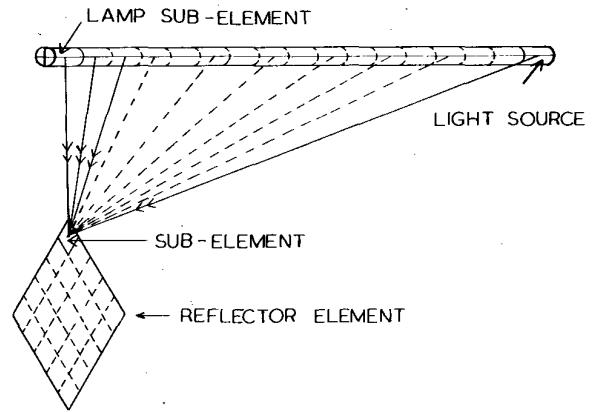


Figure 3. Lamp and reflector subelements.

vidual miniature reflector elements surrounding the lamp (see Fig. 2). There is no fixed relationship between any two reflector elements; each performs its individual function by redirecting a specific group of incident light rays into a specific direction. The method has a great advantage over reflectors that use a continuous profile. Each element can be designed individually; each can have a unique configuration in terms of curvature, vertical and lateral angle of tilt, and may be situated at a distance from the lamp which is not governed by the position of its neighbor. Figure 2 illustrates this point, showing the flexibility afforded to the designer. Only in this way can highly complex reflecting patterns be built, by the individual design of perhaps hundreds of individual reflectors, whose composite reflected light rays form the required distribution.

The flexibility of the system is not unlimited, however, as there are size constraints that limit the range of positions an element may occupy. Furthermore, there are limitations on reflector element position, as an element must not be seriously shadowed by its neighbor.

#### Computation method

It will be immediately realized that the amount of mathematics and computations involved in laying out a reflector system such as this is very considerable. This is particularly so in view of the number of elements, ranging from 286 for the low energy strobe lamp reflector to 538 for the metal halide arc lamp. Such computations can only be handled by computer.

The computer received input data consisting of the following information: (a) luminous intensity data of the bare lamp; (b) physical description of the lamp; (c) required luminous intensity distribution data for the lamp and reflector; and (d) basic information of the reflector system.

For this particular project involving underwater designs, the luminous intensity data on the bare lamp can be determined either with the lamp underwater, or in air. While readings in air are considerably simpler to make, they suffer from the disadvantage of having to be mathematically corrected for the refractive effects at the glass/water interface before

they can be used in the design. This correction is quite complex if the lamp itself consists of other than a central line source within a glass cylinder. Air measurement was used for the metal halide and quartz-iodine lamps, while underwater measurement was performed for the xenon strobes, both of which consist of multiple sources within a single glass envelope.

The physical description of the lamp as supplied to the computer consists of a mathematical model, describing the length, diameter, and position of the light producing elements, the nature of any obstructions and the nature of any optical interfaces. These interfaces are the water/glass boundary and the air/glass boundaries within the housings, or in the case of the strobe lamps, which are further complicated by being liquid-filled, the liquid/glass interfaces. The computer is programmed to take into account the effects of all optical interfaces, as well as the shadowing effect of obstructions, and the shadowing of one discharge tube by another of the strobe lamps.

Further information on the lamp supplied to the computer is the variation in luminance of a given lamp along its length and across its width. This data was collected by scanning the lamp with a luminance meter.

The required luminous intensity distribution for the lamp and reflector system was entered in terms of mathematical functions. When placed in the calculational procedure, these functions can be used to compute the luminous intensity required at any vertical and lateral angle.

The first part of the computations involves determining the distribution of light obtained from the reflector only. As mentioned, this must be performed in terms of lumens rather than luminous intensity, and therefore the table of required luminous intensity values is transformed into required lumen values within given angular zones.<sup>3,4</sup> The same is done for the direct light from the lamp; the difference between the required lumens in a given zone and the direct lumens in that zone determines the lumens which must be reflected to that zone in order to fulfill the

**Table II—Sample computer printout of reflected light from a group of reflector elements**

		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.037	0.074	0.226	0.249	0.189	0.222	0.157
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.048	0.166	0.332	0.485	0.566	0.481	0.336
		0.000	0.000	0.000	0.000	0.029	0.141	0.237	0.146	0.122	0.122	0.312	0.504	0.638	0.720	0.684
		0.000	0.000	0.000	0.013	0.088	0.170	0.520	0.715	0.544	0.264	0.192	0.243	0.354	0.569	0.558
23.0	****	<b>PATTERN BOUNDARY</b>														
		0.000	0.000	0.000	0.028	0.150	0.284	0.442	0.850	1.176	1.808	0.392	0.256	0.237	0.346	0.460
		0.000	0.000	0.000	0.015	0.098	0.264	0.323	0.539	1.088	1.406	1.078	0.714	0.391	0.326	0.444
		0.000	0.000	0.000	0.000	0.006	0.071	0.216	0.321	0.660	1.334	1.589	1.352	1.023	0.745	0.604
		0.000	0.000	0.000	0.000	0.041	0.062	0.104	0.205	0.345	0.825	1.358	1.309	1.245	0.916	0.838
		0.000	0.000	0.017	0.011	0.011	0.038	0.092	0.167	0.314	0.419	0.882	1.155	0.989	0.877	0.787
		0.000	0.000	0.029	0.034	0.028	0.050	0.041	0.097	0.165	0.368	0.533	0.914	1.085	0.807	0.753
11.5	****															
		0.000	0.000	0.000	0.018	0.035	0.039	0.087	0.087	0.120	0.222	0.390	0.632	0.961	0.814	0.748
		0.000	0.000	0.000	0.000	0.000	0.011	0.037	0.111	0.134	0.192	0.190	0.484	0.795	0.953	0.662
		0.000	0.000	0.000	0.000	0.000	0.005	0.025	0.032	0.104	0.175	0.195	0.243	0.523	0.889	0.840
		0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.038	0.058	0.109	0.187	0.234	0.339	0.642	0.606
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.040	0.085	0.199	0.320	0.348	0.376	0.793
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.140	0.218	0.389	0.445	0.579
0	****															
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.025	0.144	0.226	0.426	0.661
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.035	0.062	0.037	0.057	0.182	0.456	0.905
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.046	0.143	0.201	0.215	0.351	0.552	0.767
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.024	0.049	0.242	0.446	0.542	0.555	0.829
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.017	0.110	0.332	0.474	0.585	0.857	
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.081	0.156	0.185	0.222	0.580	0.983
-11.5	****															
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.055	0.051	0.046	0.087	0.126	0.464	1.012
		0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.018	0.018	0.011	0.042	0.065	0.237	0.630	0.966
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.003	0.000	0.022	0.102	0.323	0.748	1.188
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.044	0.155	0.493	0.889	1.261
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.048	0.132	0.336	0.709	1.114	1.700
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.050	0.182	0.379	0.693	1.161	1.614	1.960
-23.0	****															
		1.25	3.75	6.25	8.75	11.25	13.75	16.25	18.75	21.25	23.75	26.25	28.75	31.25	33.75	36.25
		<b>BETA ANGLE (LATERAL)</b>														

pattern requirements. Thus the lumens to be supplied by the reflector in any angular zone is known. The design procedure then becomes the laying out of a reflector to produce the correct lumens in each zone.

Each reflector element is designed individually. The location of the first element to be designed is supplied to the computer, and the computer builds the reflector from that starting point. An x, y, z coordinate system is assigned to the optical system (Fig. 2) and any point on the reflector can be described in terms of x, y, and z. By assigning x, y, and z values to the corner of the starting element, and by supplying its lateral and vertical tilt angles, the coordinates of the other corners are fixed, based on the assumption that the element surface is flat. The exact geometry of the element and its position with regard to the lamp therefore is known.

Both the lamp and the element are imagined to be split into many small parts. From each light source element, a band of rays (Fig. 3) is emitted and lands on a given portion of a reflector element. The intensity of these rays is known from the measured luminous intensity data and the brightness scanning of the lamp.

The luminous intensity from the lamp in a given direction is known; and from the brightness scanning of the lamp, it is known what proportion of the total intensity comes from given portions of the lamp, and thus the luminous intensity of the rays in the direction of the reflector subelement is known.

The solid angle subtended by the reflector subelement can be calculated and thus the lumens in each band of rays are known. The specular reflec-

tance of the material to be used is 70 percent, and therefore the lumens reflected by the subelement are equal to 0.7 of the incident lumens. Knowing the orientation of the reflector element with respect to the coordinate system, the direction of the emitted rays is known. The reflected lumens are assigned to this direction.

This process is repeated for every small section of the lamp, and the range of reflected light rays from the particular reflector subelement is determined, along with the lumens associated with each particular direction. The computer repeats the entire process for the next subelement, until the whole reflector element has been calculated and its reflected lumens and their directional properties determined.

The reflected light pattern as determined by computer therefore can be analyzed. The designer may proceed to the next element, or, if the light distribution is unsatisfactory, he may alter the orientation of the element. This may be achieved in two ways. First, new vertical and lateral tilt angles can be supplied and recomputation performed. The second method, however, is superior, and allows the designer to supply the computer with the amount of light pattern shift he requires. The element will then automatically be reoriented to the optimum position. The design then may proceed with subsequent elements.

After completion of a strip of elements, a printout of total reflected lumens can be examined (see Table II). The axes of the printout are vertical and lateral angle, and the figures in the tabulation represent the reflected lumens contained within the given angular zone. Changes may be made to any or a number of

**Table III—Facet by facet printout of reflector design, showing tool settings and mandril coordinates**

Element	X, Y, Z Coordinates of Element				Delta Y2	Delta X3	A1	A2	Set 1	Set 2	Screw Hole Coordinates	
	Corner-1	Corner-2	Corner-3	Corner-4							X	Y
	1	0.3000 -0.1000 1.7700	-0.0000 -0.1000 1.5140	0.3000 -0.3000 1.6300							-0.0000 -0.3000 1.3740	-0.2000
2	0.3000 0.1080 1.7690	-0.0000 0.1080 1.3720	0.3000 -0.1000 1.6280	-0.0000 -0.1000 1.2310	-0.2080	0.3000	34.1	52.9	3.6926	2.8056	0.1500	-0.3040
3	0.3000 0.3270 1.7600	-0.0000 0.3270 1.3930	0.3000 0.1080 1.6400	-0.0000 0.1080 1.2730	-0.2190	0.3000	28.7	50.7	3.6575	2.4027	0.1500	-0.5175
4	0.3000 0.5530 1.7500	-0.0000 0.5530 1.4230	0.3000 0.3260 1.6500	-0.0000 0.3260 1.3230	-0.2270	0.3000	23.8	47.5	3.5311	2.0157	0.1500	-0.7395
5	0.3000 0.7880 1.7400	-0.0000 0.7880 1.4530	0.3000 0.5530 1.6680	-0.0000 0.5530 1.3810	-0.2350	0.3000	17.0	43.7	3.3747	1.4647	0.1500	-0.9705
6	0.3000 1.1230 1.8300	-0.0000 1.1230 1.5270	0.3000 0.7880 1.7440	-0.0000 0.7880 1.4410	-0.3350	0.3000	14.4	45.3	3.4965	1.2433	0.1500	-1.2555
7	0.3000 1.4630 1.9000	-0.0000 1.4630 1.6240	0.3000 1.1230 1.8340	-0.0000 1.1230 1.5580	-0.3400	0.3000	11.0	42.6	3.3513	0.9528	0.1500	-1.5930
8	0.3000 1.9540 2.0000	-0.0000 1.9540 1.7300	0.3000 1.4630 1.9330	-0.0000 1.4630 1.6630	-0.4910	0.3000	7.8	42.0	3.3278	0.6760	0.1500	-2.0085

CONTINUED

elements in the strip to achieve the desired pattern, or further strips can be designed.

The process is repeated until the reflector is laid out. At any time during the design process, a printout can be obtained for the reflected light from a given element, a given strip, or for the entire reflector as designed to that stage. Elements may be reoriented or repositioned upon command for optimum reflector performance.

During the design, data regarding the exact alignment and position of every element is recorded in the computer memory. Upon completion of the design, a printout table is generated giving the x, y, z coordinates of the corner-points of each element, and the lateral and vertical tilt of the element. In addition, the printout provides all data required to manufacture the reflector tool, in terms of the compound angle settings of the gage blocks required by the toolmaker's double sine plate (see Table III).

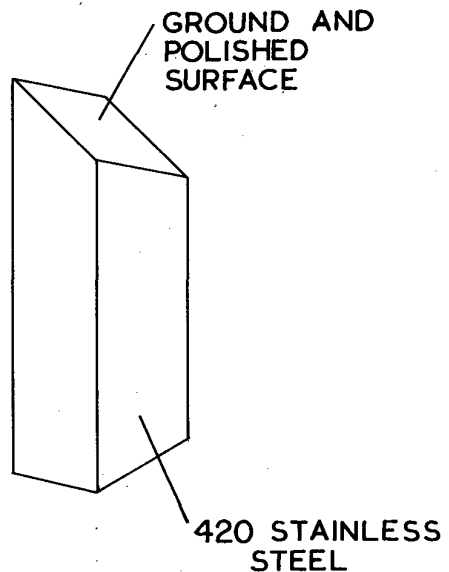
**Reflector manufacture**

As described, each reflector is formed from a multitude of individual elements. The manufacturing technique selected must depend on the precision required to reproduce the details of the design. The design technique is quite general and therefore applicable to the design of practically any form of reflector, but for the particular application it was necessary to produce a reflector with a very accurate surface configuration. Electroforming was selected as the manufacturing technique.

Prior to the forming of the reflector it was necessary to construct a stainless steel mandril with configuration in reverse to the finished reflector. Heat

treated 420 stainless steel was used for this mandril. Rectangular cross section bars with the dimensions of the required x and y coordinates were first ground to within tolerances of 0.0005 inch. The "stick" was then set up on the double sine plate and the end of the rectangular piece was ground to its compound angle (see Fig. 4). After the grinding operation, the end surface was hand polished with diamond com-

**Figure 4. Stainless steel mandril "stick" used in assembly of reflector tool. Facet angle is cut on end.**



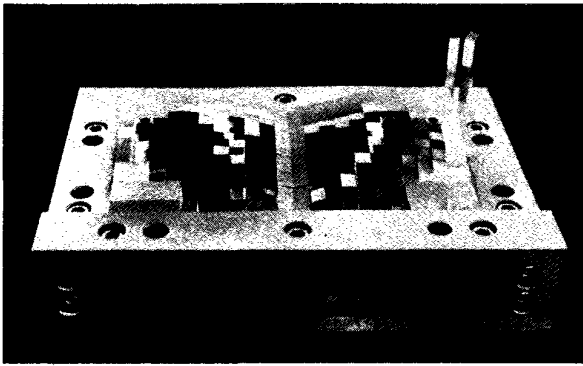


Figure 5. Reflector mandril.

pound as the final treatment. The SPI/SPE (Society of Plastic Industry/Society of Plastic Engineers) finish was less than two and the RMS (root mean square) finish as measured by a profilometer averaged approximately 0.5.

The individual sticks were then mounted vertically in a frame consisting of a back-up plate and side rails (see Fig. 5). Each stick was connected to the back-up plate with an Allen head machine screw, and the side rails tightened horizontally to force the sticks together. The final process of the finished mandril was to inspect the z dimension of the sticks.

The next step involved forming a reflector from the mandril. The process used was an electrolytic deposition of nickel by electroforming to a thickness of 0.050-inch minimum. After the buildup of the nickel on the mandril, the two were separated and the reflector as designed by the computer was formed.

The reflector was then cleaned and plated with 0.0008-inch of gold. Gold was required to stop galvanic action between the nickel and seawater. The final process was to plate 0.000015-inch of bright rhodium to form the reflective surface. The reflectors were then mounted in pairs around the light sources (Fig. 6).

Figure 6. Typical reflector system mounted.

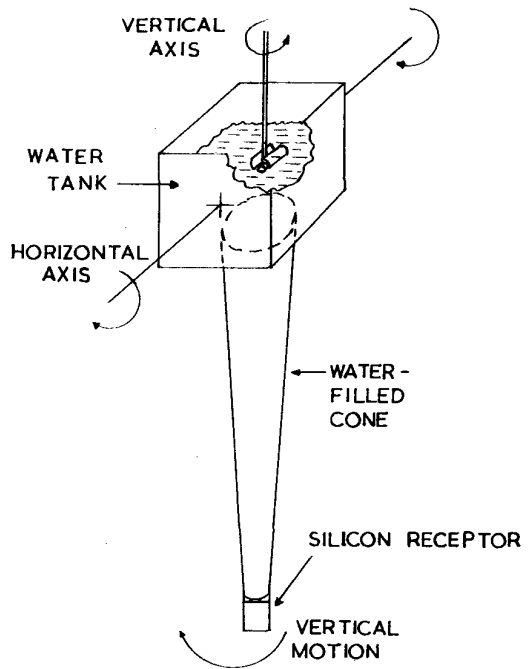
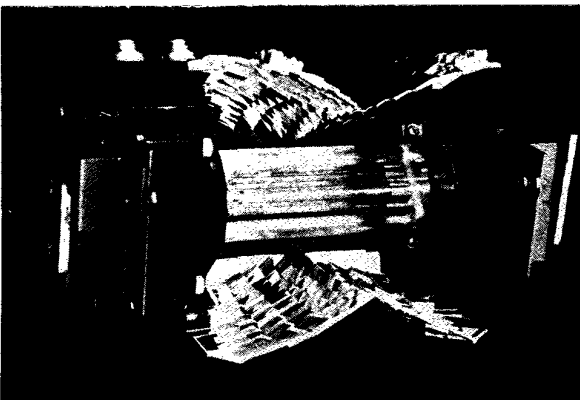


Figure 7. Schematic of underwater photometer.

#### Testing and evaluation

Normal photometric techniques could not be applied to the reflector systems for two reasons. First, two of the light sources to be used were xenon strobe lamps, emitting light pulses of approximately one millisecond. The intensity distribution photometer employed for production photometry at the authors' facility consists of selenium cells which are applicable only to the measurement of continuous or semi-continuous signals. It therefore was decided to construct another photometer using a silicon cell as its receptor that would allow the measurement of light pulses in candela-seconds, as well as normal sources in candelas. A second problem is that the photometry must be done underwater, as the optical effects created by the water are part of the design technique and ultimate use. The photometer therefore was constructed with a large water tank to facilitate such measurements when required.

Figure 7 illustrates the photometer scheme, developed from a principle by Cox,<sup>5</sup> while Fig. 8 is a photograph of the completed unit. The luminaire under test is positioned inside a steel tank, which is attached to a black velvet lined fiberglass cone with a transparent window at the end of the cone. The entire assembly is watertight, and thus the tank and cone can be filled with water, submerging the optical assembly. The silicon receptor is placed outside of the acrylic plastic window on the end of the cone, and therefore measures the light intensity in the direction of the cone axis. The test distance is approximately eight feet.

The entire tank, cone, and receptor assembly is able to pivot about a horizontal axis, and a series of readings in a vertical plane can be obtained by

moving the assembly about this axis. The vertical angular range is limited to 116 degrees when the tank is water-filled, otherwise spillage will occur. Close to 360 degrees is possible for measurements in air.

The reflector/lamp assembly is attached to a vertical bar and may be rotated 360 degrees about this vertical axis, for a full range of horizontal angles. Thus the complete field of interest may be measured.

Problems were encountered with leakage, loss of dye from the velvet lining, and the accumulation of particles and organisms in the water. The leakage was solved by the use of cork gaskets, while the dye and water particles were removed by the use of a swimming pool filter. Eventually the velvet loses its effectiveness as it turns brown due to the action of chlorine in the water, and replacement is therefore required after about three months of continuous use of the photometer when water-filled.

A further problem was experienced with the metal halide lamp due to the formation of air bubbles above the lamp. A "spider" of copper tubes was built to surround the source and force jets of water onto the lamp and reflectors, which lessened the problem substantially.

Great care was taken to exclude stray light, using velvet screens. This is particularly critical when the silicon receptor is used in the integrate mode, as it then records footcandle-seconds. A small amount of stray light therefore will cause the meter to count, giving a gradually rising reading even when the strobe tubes are not flashed.

The optical assembly under test is attached to a gantry (see Fig. 8), the gantry being on wheels and a track. This allows the gantry and lamp to be moved across the laboratory to be positioned over a second and larger water tank. This tank has a coordinate system painted on the bottom, and can be used for photographing intensity patterns.

### Results and conclusions

In general, very good agreement was obtained between computer predicted results and the actual patterns obtained. In three out of the four optical systems, contractual guarantees of luminous intensity distribution and efficiency were met with the first reflectors produced, while the fourth was obtained with some realignments and modifications.

The final test of the optical systems will be the quality of the photographs that they produce, which involves the lenses of the cameras, the film response, and the scattering effect of the water, as well as the reflector performance. The work so far has indicated the value of the design techniques by showing the correlation of anticipated and actual results. Such methods show great possibility for the application to all forms of reflector design, including roadway, area, and floodlighting luminaires as well as those described above.

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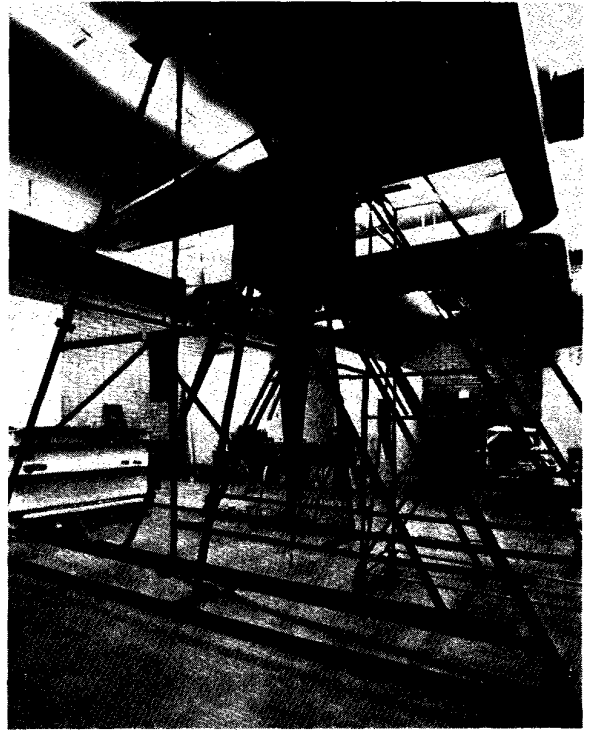


Figure 8. Underwater photometer.

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3. L. B. W. Jolley, J. M. Waldram, and G. H. Wilson, *Theory and Design of Illuminating Engineering Equipment*, Chapman-Hall, London, 1930.
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5. Communication from Dr. Henry Cox, Westinghouse Oceanic Research Center, Annapolis, Maryland.

### DISCUSSION

J. B. ARENS:\* Congratulations to the authors for illustrating how the basically straightforward, but enormously tedious job of designing a complex reflector can be handled in a sophisticated manner by what seems to be getting quite an old and reliable friend of ours, the computer.

There are several items I would like the authors to comment on:

(1) If the scatter effects produced by suspended particles in the water can be minimized by applying a mathematical treatment to the reflector design, the particle size and particle density should be known. Since one could expect these two parameters to vary considerably with location—for example the Atlantic coast off New Jersey versus the waters near Antarctica—was any particular size and density of particles selected for the mathematical treatment? If the reflector would have been designed without this consideration, how much of an error would have possibly been introduced, and would this error have been greater than the difference found between computer predicted results and actual results obtained during the photometric testing? Could a similar

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rationale be applied to outdoor lighting equipment designed to better perform under severe weather conditions, such as rain, fog, or snow, by allowing an alternate set of, say, driving lights on a car, or a secondary optical system in a street-lighting fixture, to take the place of the standard equipment and provide better visibility?

(2) The authors stated that the floodlight design used an optical system free-flooded with seawater. I interpret this to mean the lamps, as well as the reflectors, were in contact with seawater. How did the authors compensate for the cooling effect of the water around the metal halide and the quartz-iodine lamps? Are not these sources extremely temperature sensitive? Also, what effect did orientation of the floodlight, which I assume is handheld and portable, have on the performance with the metal halide lamp?

(3) The effective reflector surface is composed of small reflector elements oriented principally in the x-y plane. Since there exist surfaces also in the x-z and y-z planes, which are made up of the sides of the rectangular cross section bars, how have the authors treated the reflection produced by these small sections? Also, would the authors care to comment on the possible use of this design concept for larger size reflectors—say a reflector used with a 400-watt high-pressure sodium (HPS) lamp for roadway lighting—keeping in mind that a less costly method of manufacturing, such as hydroforming, would have to be used?

K. E. FAIRBANKS:<sup>†</sup> The authors' presentation describes a unique lighting application that required a unique computer analysis and design with the resultant solution being a unique approach to a reflector configuration. Based on the success of the design program it would be difficult to criticize the concepts and procedures indicated in this paper. However, in the same vein, it is difficult to imagine a commercial or practical application where a similar reflector configuration could be employed. Maintenance considerations alone would preclude such a multifaceted reflector from being used in a street-lighting luminaire.

With the above in mind, would the authors comment on the following. Did the multifaceted reflector prove to be excellent in overall efficiency or was performance rated in terms of meeting the original design criteria for an intensity distribution pattern regardless of luminaire efficiency? Would the placing of a design constraint that all reflector segments join smoothly with adjacent segments have resulted in a more efficient reflector that would have met the design criteria but perhaps with less precision? Would this design constraint have made the overall computer analysis and design more difficult and time consuming? I assume that the ground and polished reflector surfaces are flat planes in this design. Would an attempt to apply distinctive curvatures to each segment again complicate the design procedures? Is it possible to provide any insight into the length of time it would take the computer to analyze each element, each strip, and the complete reflector? Obviously the number and size of reflector elements would materially affect both the precision and performance of the reflector and the costs of the computer design.

M. E. KECK:<sup>‡</sup> The authors have presented an interesting and readable paper concerning the design, manufacture, and testing of a particular very specialized reflector for use in a very specialized application. They state in at least two places that the methods used show a great possibility for application to all forms of reflector design such as roadway, area and floodlighting luminaires. There is no question that the techniques can be applied to such reflectors. There is a question, however, as to whether or not the techniques described would produce a superior reflector to a well designed reflector using a continuous curved surface or a few continuous curved surfaces with steps or risers between them.

I am concerned that the authors may leave the impression that a reflector designed with many flat facets is always superior to one designed with a few continuously curved sections. It is my opinion that the reflector described could be improved if two things could have been done: (1) the facets could have been curved rather than flat; and (2) the number of facets, if curved, could be reduced, thus reducing the uncontrolled light from the corners of the junctions between facets and of course reducing the shadowing effect of the steps between facets as stated by the authors.

<sup>†</sup> Gardco Mfg. Inc., San Leandro, California.

<sup>‡</sup> Westinghouse Electric Corp., Vicksburg, Mississippi.

I do not wish to imply that the practical state of the art in design and manufacturing techniques to accomplish these objectives is practical today and that the solution achieved by the authors could easily be improved upon. It is my opinion, however, that in a few years the state of the art of both the design techniques and manufacturing techniques will make such an improvement practical.

The ultimate reflector for roadway, area, and floodlighting luminaires will therefore consist of a minimum of large continuously curved facets and will not consist of a large number of small flat faced facets. Many of today's reflectors look as if they have already achieved this ultimate result; however, the large curved facets of today's reflectors may often be simple paraboloids, ellipsoids or other simple surfaces of the second degree which may or may not be the best surface to direct the light as desired. The application of techniques described by the author may well improve such reflectors but we must not reach the conclusion that the ultimate reflector will consist of a multitude of flat faced facets.

J. S. SCHRUBEN:<sup>§</sup> This paper is a lucid description of engineering techniques used to design reflectors to meet very difficult specifications. I, however, would be interested in further amplification on the method used to minimize light scattering by the water particles.

The authors have demonstrated that their method of adjusting reflecting facets by computer simulation is effective for asymmetric designs. But is it the only way as they claim? Unfortunately, the authors' Reference 3 does not provide an alternative unafaceted approach. Although Jolley, Waldram, and Wilson' claim to show how to obtain smooth asymmetric reflectors, their method is really only suited for faceted reflectors such as the authors designed, or at best fluted reflectors. Not only are their equations for the normals to the reflecting elements incorrect, but they basically overdetermine the problem. They look only for reflecting surfaces which reflect rays emitted in a meridional plane into another meridional plane. It would be an unusual asymmetric surface that would have this property.

The asymmetric reflector-design problem may be described mathematically by a partial differential equation.<sup>2</sup> Solutions to this equation can be expected to exist for "highly complex reflecting patterns." Consequently so would smooth reflectors exist in principle provided the reflectors are allowed to be sufficiently large relative to the source. To find a solution is admittedly not an easy problem. For comparatively large sources there may indeed be no exact solution to the problem. Compromises must be made. Faceted reflectors are analogous to Fresnel lenses which are commonly used to make more compact optical systems. However, lenses may be placed as close to the source as heating requirements allow, whereas the source itself will tend to interfere with light reflected from a close-by reflector. The edges of both refracting and reflecting facets block and scatter emitted light and thereby lower the efficient utilization of light and cause glare. An optimum reflector would consequently be as smooth as possible.

If perhaps the authors have not obtained the optimum answer, they certainly have solved the problem presented to them. In view of the magnitude of this task, they deserve much praise.

## References

1. L. B. W. Jolley, J. M. Waldram, and G. H. Wilson, *The Theory and Design of Illuminating Engineering Equipment*, John Wiley and Sons, Inc., New York, 1931.
2. J. S. Schruben, "Formulation of a reflector-design problem for a lighting fixture," *Journal of the Optical Society of America*, Vol. 62, No. 12, December 1972, p. 1498.

D. A. TOENJES:<sup>||</sup> Would it be possible to reduce the depths of the individual vertical sides of adjoining reflector facets, by changing the square elements to hexagonal shapes? They could then be lined up in a staggered arrangement, still using the same x, y coordinates for computer calculation. (This might also offer a physical advantage, in that the reflector corners would become obtuse 120-degree angles, so the facet corners would not be so sharp.)

<sup>§</sup> Westinghouse Research Laboratories, Pittsburgh, Pennsylvania.

<sup>||</sup> Spero Electric Corp., Cleveland, Ohio.



**AUTHORS:** The authors wish to thank the discussers for their interesting presentations.

The comments by Messrs. Fairbanks, Keck and Arens relating to the design of reflectors for commercial applications are accurate. The authors do not believe that a direct application of the reflectors as presented would offer a step forward in such applications. It must be kept in mind, however, that a design principle has been evolved, which has been shown to be capable of producing reflectors for meeting highly complicated specifications. It does not seem unreasonable that such principles could be applied to commercial products, although the end result would be considerably different. In particular, as pointed out by the discussers, any approach for an area or roadway luminaire would require a much lesser number of facets, or preferably with the facets blended to form a smooth surface for practicality of manufacture.

The authors do not feel that an approach using smooth reflectors in this project would have allowed the same performance to be obtained, primarily due to size limitations. An extremely small volume was allowed for each optical system, and as pointed out by Dr. Schruben, a faceted reflector system is equivalent to a Fresnel lens system, in offering a more compact design while retaining desirable contours.

It is possible that the performance of the systems could have been improved by using curved facet surfaces instead of flat. A considerable increase in manufacturing cost would accompany such an approach, however, and flat facets, therefore, were used. As stated by Mr. Keck, however, such an approach may be possible in the future with improved design and manufacturing methods.

In answer to Mr. Fairbank's question regarding performance, this was rated in terms of both distribution and efficiency. The

distribution limitations imposed, however, were more serious than those of efficiency, and output was sacrificed in many instances where the two were in conflict.

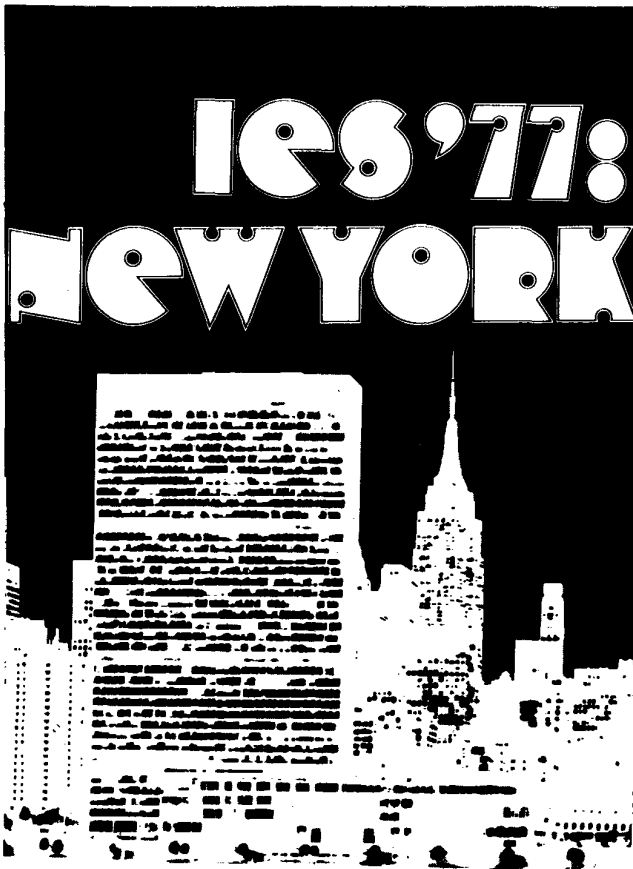
Regarding the length of time taken by the computer to analyze one reflector system, this varied in accordance with reflector size and lamp size. Typical runs were in the order of 120 seconds of central processor time on the CDC6600 computer. Computation time could have been either increased or decreased by using smooth reflector contours, depending upon the mathematical approach used.

Concerning Mr. Arens' question on suspended particles in the seawater, this was taken into account by the agency issuing the design criteria to the authors, and the authors were not directly involved in the effort. It is our understanding that a seawater of particular interest or median characteristics was used in determining the water scattering effects, and that the required isocandela patterns are such as to minimize the effects. The point regarding distribution patterns for inclement weather in roadway situations could open some interesting possibilities.

The cooling effect of the water is taken into account by determining the light distributions underwater, in such a way that this cooling is present during photometry.

All equations used in the mathematical analysis of the problems were generated from first principles by the authors, and those stated in Reference 3 of the paper as being incorrect by Dr. Schruben were not employed.

The suggestion of Mr. Toenjes is interesting. The authors have some experience of molding with hexagonal section bars and have found this approach useful. It is a possibility to be kept in mind for future designs.



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