THE HARBOR BRANCH FOUNDATION ARC LIGHT

- A Comprehensive Account -

By

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Harbor Branch Foundation, Inc.

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Research and Development
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ABSTRACT

The Harbor Branch arc light provides a powerful light source, over the entire spectrum of visible light, for underwater visual and television observation. This paper traces the development and refinements of this light. A comprehensive electronic analysis, and unique engineering solutions to mechanical packaging are detailed.

Acknowledgments --

The opportunity to be associated with the Research and Development department at Harbor Branch Foundation, Inc. has been personally rewarding and worthwhile, for which I thank Harbor Branch. The individuals I involved in brainpicking, consultation, and advice seeking for this project gave of themselves readily and willingly, helpfully and jovially. Thank you Chris Tietze, Sam Vulih, Dennis Green, David Clayton, Pete Gingras, Kathy Inman, Bonnie Kerr, and Jack Martin.

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ILLUSTRATIONS

1.0 INTRODUCTION

An important aspect of the research conducted at Harbor Branch involves in situ observation of various facets of the ocean. Research personnel in the field use visual inspection and image recording techniques consisting of still photography and video tape recordings. A proper lighting system is essential to any method of observation at depth in the ocean where natural light has been absorbed by the water column. Currently, the video equipment on the JOHNSON-SEA-LINK (JSL) submersibles is both black and white and color. True to life images, such as for television systems and personal observation, require a continuous and abundant light source of uniform intensity over the visible light spectrum. As part of the Harbor Branch Foundation's engineering support for scientific study, such a lighting system was developed, and is the subject of this report. The light is designed primarily for use with color television equipment and for visual observation at greater distances than are possible with existing submarine lights. Engineering criteria for the light are as follows:

1. Uniform intensity over the visible spectra, i.e., white light.
2. Sixty degree angle illuminating cone of uniform intensity.
3. Sufficient intensity for color TV.

4. Operational compatibility with JOHNSON-SEA-LINK power system.

5. Human engineered for ease of operation.

The alternative sources of light were researched. A proposed xenon arc light system was shown to best fulfill the lighting needs of a color TV system. The lamp itself provides a high intensity white light source with a color temperature of 6000°K, as specified by the manufacturer. This point source of light is readily adaptable to mounting in an ellipsoidal reflector designed to project a 60° cone of illumination. The selected lamp is rated at 1 kw and provides high output in the visible portion of the spectrum (400 nm - 700 nm), as well as infrared and ultraviolet.

2.0 HISTORY: ARC LIGHT I

2.1 INITIAL DEVELOPMENT

The project began by extending a research grant to the School of Engineering and Applied Science at Columbia University, in the city of New York, in care of Charles Sheer, Senior Research Associate of the Chemical Engineering Research Laboratory. The agreement charged Mr. Sheer with developing the technology required to meet the design criteria of the arc lamp. First and foremost was the design of lamp operating circuitry. An extended time period passed in which results were not forthcoming. Unforeseen technical problems, principally attributed to the low voltage (28v) battery supply limitation on JSL were cited as the cause of the delay. Later, another contractor, Streamlight, Inc., was commissioned by Harbor Branch to continue development of the lamp, whereupon the Columbia University project was halted.

Mr. Robert Strow was the design engineer at Streamlight to whom the Harbor Branch arc light project was assigned. At about midway to completion of the light, Mr. Strow left Streamlight. He continued development as a consultant. One functioning light, and one partially assembled light, were delivered to Harbor Branch. Detailed literature and schematics accompanied the units. The electronics were housed in a pressure compensating cylindrical enclosure. This design was the result of close collaboration between Mr. Strow and

Mr. Chris Tietze, Manager of Mechanical Engineering for the Research and Development Department at Harbor Branch.

2.2 EVOLUTION AT HARBOR BRANCH

The prototype arc lamps delivered to Harbor Branch Foundation were the first known application of illumination by continuous xenon short arc radiation to the ocean environment. As is frequently the case in the initial implementation of prototype systems, certain modifications are required either for improved performance or rectification of unforeseen complications. The submersible arc lights were no exception. Four noteworthy changes occurred in the unit at Harbor Branch over a period of time, prior to the author receiving the light for repair.

2.21 LAMP REMOVED FROM OIL IMMERSION

The unit was contained in a pressure compensating tube. This housing was oil filled and exposed to the pressure of depth via a flexible diaphragm mounted on the flat aft endbell. A quarter inch clear acrylic plate provided the seawater/oil interface for the lamp. Overall simplification of the structure accrued from this design, in terms of reliability, minimal weight and ease of construction. The exposure of components to pressure, however, did require certain damage prevention measures. Large power transistors were pressure compensated by means of a minute hole in each casing. For the same reason, a flexible bladder was affixed to electrolytic capacitors, sealing the electrolyte inside. The pressure compensating fluid was a silicon based oil, specifically, a dimethyl-polysiloxane, manufactured by Dow Corning as Dow Corning 200 Dielectric Fluid. The fluid color was clear, had a specified viscosity of 50cs and a useful temperature range of -40 to 205°C. Electrically, the fluid exhibits excellent insulation characteristics with a dielectric strength of 430 volts/mil. Physically, the submergence of components in oil provided far better heat dissipation than would an air filled cannister.

Several tests of several hours each were conducted in a test tank and pressure chamber. The lamp satisfactorily passed the pressure test, remaining operationally intact. A slight discoloration of the oil appeared, however, progressing from clear to light yellow to a yellowish brown. This occurrence was unacceptable, as it impeded light output, and put particles with possible conductivity in the oil. Since the oil was allowed to freely circulate by convection within the container, pinpointing the source of the discoloration was difficult. The manufacturer eliminated exposure to ultra-violet from the lamp as a possible cause. The possibility was considered that electrolyte from a capacitor, a highly corrosive substance, was leaking into the oil, attacking metal such as transistor casings, that would in turn impart rust particles to the oil. Considered, also, was the possibility that color was leached out of paper, wire insulation, or other material in the lamp in a reaction with the oil. The operating temperature of the lamp was undetermined at the time, but has since been specified by the manufacturer to be between 600 and 800°C at the arc, in air. The useful temperature range of the oil was rated as 205°C, indicating the most likely cause of the discoloration was the excessive lamp temperature charring the oil. A novel reworking of the lamp end of the housing resolved the problem. The plexiglass port was eliminated, placing the lamp in direct exposure to seawater for cooling purposes, thus making the reflector the new seawater/oil interface. The anodic lamp contact penetrated the base of the reflector into the oil where an electrical connection was made. The quartz arm was cemented to the reflector, prior to this contact, with a ceramic cement. RTV sealed the porous cement from seawater. The cement was chosen for its ability to withstand high temperature and because the thermal expansion rate was similar to the quartz. This setup provided the physical support for the lamp, and electrical insulation from seawater. The cathodic lamp contact was brought by wire to a small hole in the side of the reflector to which another contact pin in the oil completed the circuit path. The wire exposed to seawater in the reflector was insulated with liquid dip vinyl. The lamp operated successfully.

2.22 REVERSE POLARITY BLOCKING DIODES ADDED

In operation, power was received through two identical underwater pluggable Electro Oceanic penetrators. To guard against the possibility of accidentally reversing the polarity of the connections, with disastrous consequences, two large blocking diodes were added to the circuitry on the positive input. The diodes allowed current to flow only if the penetrators were of proper polarity.

2.23 POWER SAVING CHOKE REMOVED

The original circuit design included a large choke for power saving purposes. However, the noise generated by this coil had such an adverse affect on other electrical systems of the JSL that it was deemed intolerable. Permanent removal of the choke reduced, but did not eliminate, the noise problems.

2.24 NOISE SUPPRESSION ADDED

Suppression of electrical noise in JSL generated by the arc light was accomplished by introducing a parallel capacitor and resistor across the power input. Through proper choice of the RC factor, the noise was contained within the unit.

2.3 CONDITION OF LIGHT REQUIRING REPAIR

The light, see figures 1a and 1b, was turned over to JSL Operations only to discover the previously mentioned "bugs." During the debugging process, the light acquired a reputation of unreliability. Typically it was used in operation for a short time and sent back to R&D for further refinement. The light operated satisfactorily for approximately 15 operational hours. Then, while running at 1000 feet of depth, the lamp arm snapped off close to the reflector. This catastrophic failure once again returned the unit to R&D. A new lamp was mounted in a reflector but the light failed to operate.

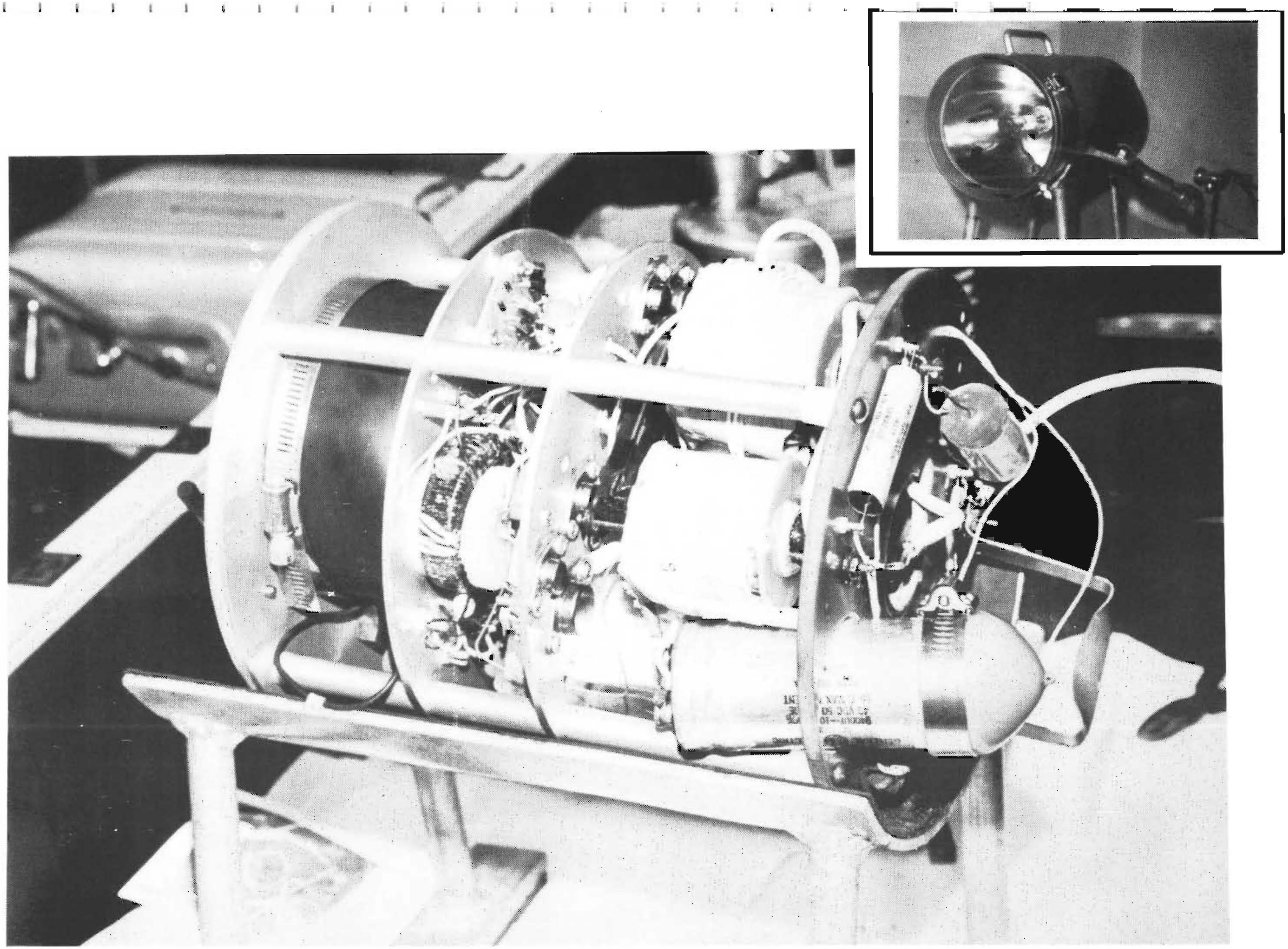
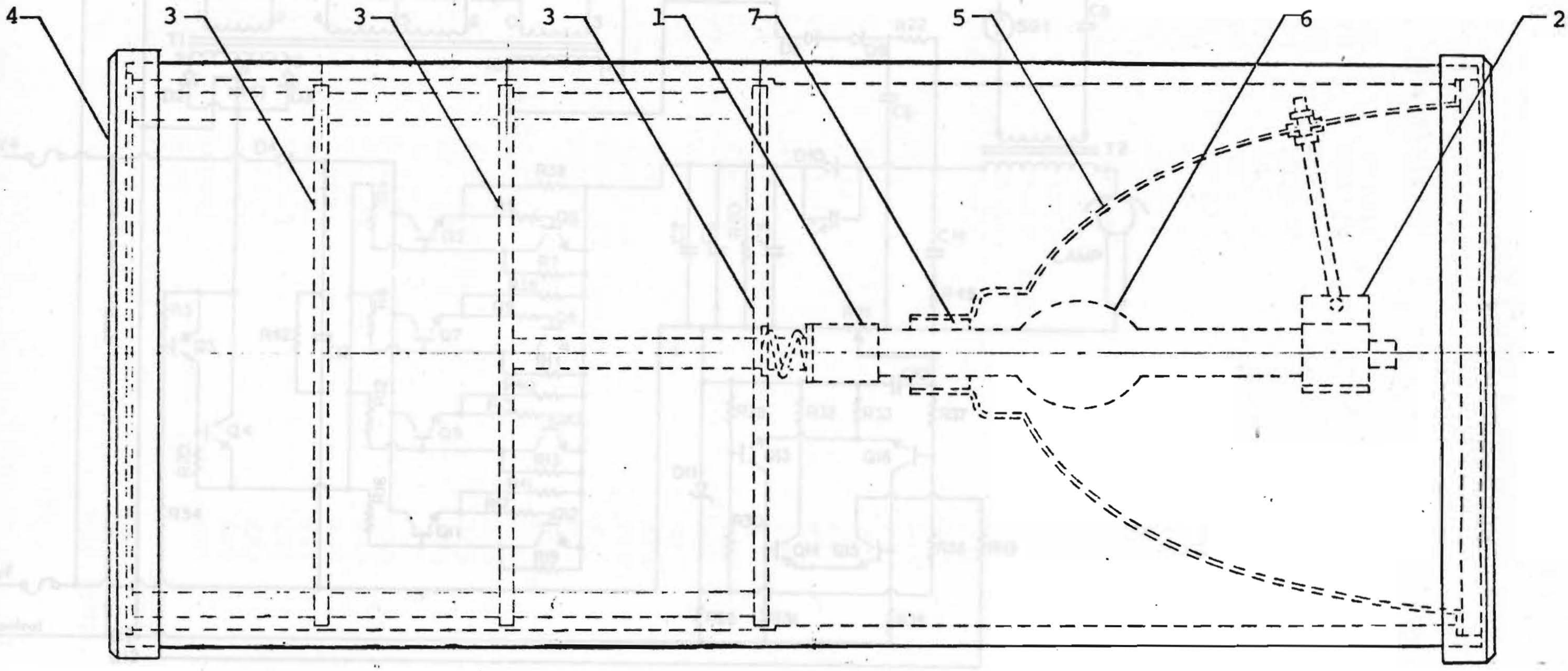
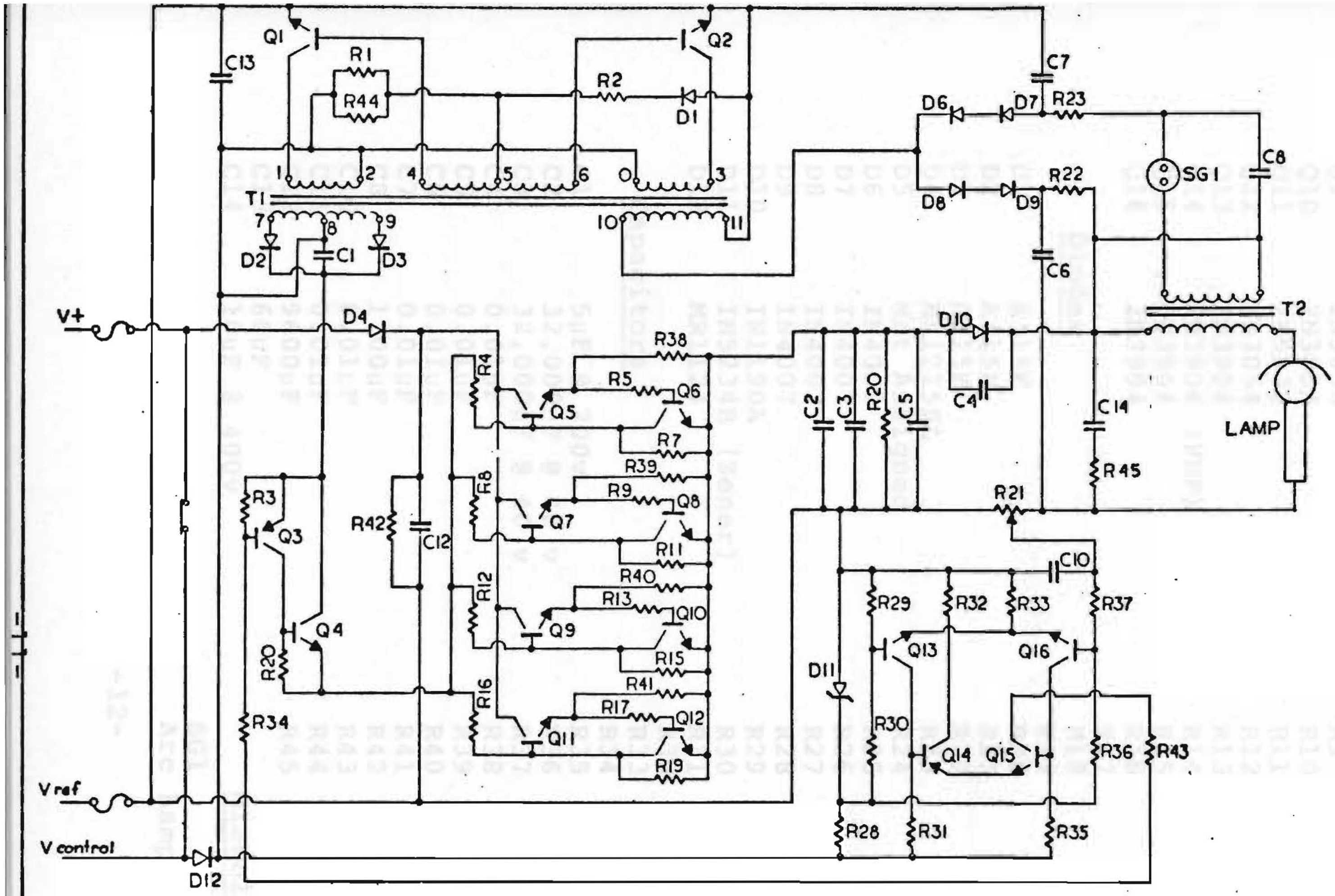


FIGURE 1A: ARC LIGHT I
INTERNAL AND EXTERNAL VIEWS



1. Anodic contact
2. Cathodic contact
3. Component mounting bulkheads
4. Aft endbell
5. Reflector, internal oil and external seawater interface
6. Lamp, seawater exposed
7. Ceramic cement seal

Figure 1b: Arc Light I Skeletal Assembly Layout



QTY	QTY	ITEM NO	PART NUMBER	DESCRIPTION	STOCK SIZE	MATERIAL

PARTS LIST

NEXT ASSEMBLY

GENERAL NOTES: REMOVE ALL BURRS AND BREAK ALL SHARP EDGES. ALL MACHINED SURFACES TO BE 125. FINISH UNLESS OTHERWISE NOTED. DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED

TOLERANCES

HARBOR BRANCH FOUNDATION, INC.

PROJECT TITLE: SUPPORT EQUIPMENT

TITLE: WIRING DIAGRAM ZENON ARC LIGHT SUB I & II

DRAWN R. QUINN DATE 4-23-79

DWG SIZE C

DRAWING NUMBER C-14-1763

SCALE NONE

SHEET 1 OF 1

Figure 2: Arc Light Electronics Schematic

Figure 3

ARC LIGHT ELECTRONICS PARTS LIST

Transistors

Q1	2N4240
Q2	2N4240
Q3	2N6211
Q4	2N5038
Q5	2N5038
Q6	2N3054
Q7	2N5038
Q8	2N3054
Q9	2N5038
Q10	2N3054
Q11	2N5038
Q12	2N3054
Q13	2N3904
Q14	2N3906 (PNP)
Q15	2N3904
Q16	2N3904

Diodes

D1	A115F
D2	A115F
D3	A115F
D4	MR1215SL
D5	Not Assigned
D6	IN4007
D7	IN4007
D8	IN4007
D9	IN4007
D10	IN1190A
D11	IN5234B (Zener)
D12	MR1124

Capacitors

C1	5μF @ 200v
C2	32,000μF @ 40 v
C3	32,000μF @ 40 v
C4	0.01μF
C5	0.01μF
C6	0.01μF
C7	0.01μF
C8	1.00μF
C10	0.01μF
C11	0.01μF
C12	9600μF
C13	68μF
C14	10μF @ 400v

Resistors

R1	1500Ω	½w
R2	15Ω	½w
R3	1500Ω	½w
R4	10Ω	10w
R5	2Ω	1½w
R6	15Ω	½w
R7	150Ω	½w
R8	10Ω	10w
R9	2Ω	1½w
R10	Not assigned	
R11	150Ω	½w
R12	10Ω	10w
R13	2Ω	1½w
R14	Not assigned	
R15	150Ω	½w
R16	10Ω	10w
R17	2Ω	1½w
R18	Not assigned	
R19	150Ω	½w
R20	3KΩ	10w
R21	0.007Ω	Custom Made
R22	100Ω	½w
R23	4.7MΩ	1w
R24	Not assigned	
R25	Not assigned	
R26	Not assigned	
R27	Not assigned	
R28	3.9KΩ	½w
R29	11KΩ	½w
R30	10KΩ	½w
R31	10KΩ	½w
R32	1.2KΩ	½w
R33	3.9KΩ	½w
R34	33KΩ	½w
R35	10KΩ	½w
R36	10KΩ	½w
R37	10KΩ	½w
R38	0.05Ω	10w
R39	0.05Ω	10w
R40	0.05Ω	10w
R41	0.05Ω	10w
R42	10KΩ	½w
R43	1.2KΩ	½w
R44	1500Ω	½w
R45	15Ω	½w

Miscellaneous

SG1	CG-800L	Spark Gap
Arc Lamp	976C10	Canrad Hanovia

3.0 ANALYSIS

3.1 OVERVIEW

This section introduces the obstacles encountered in the understanding and repair of Arc Light I, as well as the analysis used for their rectification. A more detailed account occurs in Section 3.2.

3.11 HANDLING HAZARDS

The nature of the arc light presents certain physical dangers that one must be aware and cautious of at all times. The pure quartz lamp (bulb) is pressurized to 400 psi in its non-energized state, representing an explosion hazard. In addition, high voltages (800v sustained for a time, 25,000v instantaneous spike) and high current (40 amps) were present within the circuitry. Sam Vulih, Electrical Engineer for Research and Development, and the author were assigned to investigate the light as a team.

3.12 PHYSICAL ANALYSIS FOR SCHEMATIC VERIFICATION

The first step of the investigation involved a review of available arc light information. The records proved to be incomplete and disorganized. The various changes that had occurred in the light over time were not thoroughly documented, and did not necessarily reflect the present condition of the unit.

A physical analysis was conducted to verify existing schematics and to ensure accurate knowledge of the current state of the light. From this analysis, a thorough schematic was produced, see figures 2 and 3, and an electronic analysis began.

The starting circuit for the lamp is unique in design, and is held under patent by Mr. Strow. Two coils of major consequence in the unit were also designed, and hand wound by Mr. Strow; however, no record of their characteristics were available at the time. This caused difficulty in completing an analysis by creating an area of speculation that could not be proved without further information. For the most part, though, the theory of operation was deduced.

The task of determining why the light failed to function with a fresh lamp was pursued. The unit was carefully set up on a test bench with as much separation between component plates as was possible. Insulating spacers between the plates guarded against the almost certain disaster that would occur should the plates contact one another with the power on. Verification of the theory of operation began by probing appropriate nodes for actual voltage levels, and comparing them with calculated values. The purpose of this plan was to find either isolated or gross inconsistencies, indicating, respectively, faulty components or indicating an incorrectly deduced theory, i.e., correlation of theory and reality. Reality proved to be gray in that most sections of the circuit showed isolated inconsistencies, while the current monitoring circuit, termed feedback sampler, was grossly inconsistent. The theory was reevaluated and determined to be correct. The remainder of the circuitry was examined, letting the feedback sampler stand. A subsequent determination showed that the misleading values were present because the feedback sampler, as it was, had a negligible overall effect.

3.13 SUCCESSFUL TURN ON TRIAL

The test setup lamp was successfully used previously on the submersible; however, the possibility that it was now faulty in some way was considered. A dummy load, with power handling and start up characteristics similar to an arc lamp, was needed. This proved difficult to find, given the unique characteristics of arc lamps. Fortunately, though, at this point another lamp was located. The new lamp was inserted into the circuit and powered up. It ignited and remained lit. Success.

3.14 EPOXY CONDUCTIVITY PROBLEM

The expense of a lamp, and time required to mount it in a reflector is significant, prompting an attempt at rejuvenating the first lamp. Physically, the lamp appeared intact. The only discernible difference from the functioning lamp was the presence of an epoxy band extending from the anodic contact to the reflector, covering the quartz arm at that point. Using a megohm continuity checker, with the probe set at the maximum of 1000v for material breakdown, the resistivity of the lamp/

reflector units were compared. The resistance between the contacts and the reflector of the functioning lamp read infinity. The non-functioning lamp showed a resistance of 100KΩ between the anodic contact and the reflector. While this was certainly a high value, it evidently was not high enough to allow the lamp to start. It was hypothesized that high voltages on the starting circuit capacitors were drained through the epoxy before sufficient voltage levels could be reached to ionize the xenon gas and arc the gap.

3.15 VISIT BY DESIGNER, ROBERT STROW

As the circuit analysis continued, contact was established with Mr. Strow, who was very friendly, helpful and valuable as an information resource. As luck would have it, Mr. Strow mentioned he had established plans to be in the proximity of Harbor Branch, and accepted an invitation to spend a day answering questions and explaining his circuitry. At the time of his arrival, the light was functioning with the second lamp. In addition to his knowledge, Mr. Strow brought the information necessary to complete our records, and our analysis.

3.16 LEAKAGE AND GAS FORMATION PROBLEMS

The conductivity problem with the first reflector mounted arc lamp was corrected, as explained in the following section. The unit was reassembled, filled with oil, and submerged in an open surface test tank. The tank had a window on one side, and with the aid of a dark welding mask, allowed direct observation of the light in operation.

Two problems presented themselves at this time. First, a substance was observed leaking from the base of the reflector when the light was on. It rose to the surface as a liquid and/or as a bubble of smoky vapor. The substance was thought to be either melted epoxy, present as a sealer, or Dow Corning 200 fluid from inside the housing.

Secondly, bubbles of clean gas were observed forming on the bulbous part of the lamp. These bubbles were dissolved gases driven from solution in the water due to the intense heat of the bulb. Bubble creation was a natural and ongoing process.

To this point, no satisfactory explanation of why the bulb cracked while in operation existed. The light is typically mounted with the lamp oriented below horizontal. It was hypothesized that the bubbles collected and became trapped in the base of the reflector, displacing cooling water. Shortly, a sharp heat gradient would be created, severe enough to cause failure in the quartz. This problem was inherent to this housing scheme.

3.2 DETAILED VIEW

The arc light as a system involves both mechanical and electronic detail. The electronic circuitry, refer to figures 3 and 4, is described by the designer, Mr. Strow. The description confirms, and is confirmed, by the circuit analysis completed at Harbor Branch Foundation prior to the receipt of Mr. Strow's writing. This writing is reproduced as follows:

3.21 ELECTRONIC ANALYSIS

3.211 Theory of Operation

In describing the operation of the underwater xenon light, we must understand the operation of an xenon lamp. The lamp has starting and operating characteristics which are far different from any incandescent lamp. Since the xenon lamp has no filament, a conductive path must be created in the lamp. To do this, a high voltage must be applied across the lamp electrodes, thus ionizing the gas and rendering it conductive. After the ionized path is created, the lamp electrodes must be heated so that ionic emission can occur, enabling the lamp to run at its normal operating voltage. Without this conditioning of the electrodes, the lamp will merely flash, never obtaining a steady state running condition. The electrode heating is accomplished thru a circuit technique which is proprietary to Streamlight, Inc. under patent number 3922584.

Once lit, the lamp exhibits a negative resistance with lamp current increasing greatly with little or no change in lamp voltage. To overcome this characteristic the light is designed with a current limiting circuit.

3.212 Multivibrator Converter

The converter is used to generate the various voltages required during the ignition and starting sequence and the drive voltage for the pass transistors.

The converter circuit is a common multivibrator design. It is composed of transformer T1, transistors Q1 and 2 and bias and feedback elements, resistors R1||R44, R2 and diode D1. The circuit has an operating frequency of 1 to 2 kilohertz and is a function of the input voltage.

There are two independent secondary windings; the high voltage winding 10-11 provides about 400 volts AC and winding 7-8-9 provides about 10 volts.

The 400 volts is rectified by D6 and 7 to provide a -400 volt DC supply and by D8 and 9 to provide a +400 volt DC supply. The -400 volts is one of the potentials needed by the ignition circuit, while the +400 volts is used in both the ignition circuit and as part of the starting circuit in charging initial dump capacitor C14.

The drive winding 7-8-9 is full wave rectified and added to the primary input voltage. This circuit provides a potential about 10 volts higher than the input supply. This circuit provides two functions, first charging capacitors C2 and 3 to a potential high enough, +35 volts, to allow secondary electrode heating during the starting sequence, and second to provide the base drive necessary for the pass transistor regulator during the run mode.

3.213 Feedback Sampler and Actuator Current Regulator

The current [regulation circuit] is a pass transistor type controlled by a differential amplifier, [the feedback sampler]. The reference for the regulator is a 6.2 volt zener diode, D11. The reference is divided down by resistors R29 and 30 to provide one input to the differential amplifier, Q13 and 16. The second input is derived by divider R36 and 37 and the added voltage generated across sense resistor R21, which is a function of lamp current. The differential output of the amplifier controls the cascoded amplifier of transistor Q14 and 15.

3.214 Current Amplifier

The circuit arrangement acts as a variable resistor controlling the base drive to control transistors Q3 and 4, [the feedback actuator], which in turn control the pass transistors Q5, 7, 9, and 11. The pass transistors are arranged as four parallel circuits. Each of these transistors are in turn limited to a maximum current of approximately 15 amperes. When the current approaches the 15 ampere level the limiting transistors, Q6, 8, 10 and 12 are turned on, thus shunting the base drive of the main pass transistors.

3.215 Starting Circuit

With these circuit elements described the sequence of events in the actual circuit will be outlined.

Primary power is applied to the appropriate power plugs; however, nothing will happen until the control plug contacts are shorted. Shorting these contacts applies the positive primary voltage to both the converter and regulator circuits.

The regulator sensing the lamp current is low, so current at this time allows the drive control transistor, Q4, to be turned on hard. Because of the blocking action of diode D4, the drive voltage can be added to the supply voltage. This results in the charging of capacitors C2 and 3 to over 35 volts, a potential required in the lamp starting sequence.

During this time the high voltage portion of the converter is charging two other capacitors in the ignition circuit. Capacitor C14 and one side of capacitor C8 are charged to a voltage in excess of 250 volts by the positive high voltage supply. The negative high voltage supply is connected to the apparent doubling of the voltage across C8. As the voltage across C8 builds, it approaches the breakdown voltage of the spark gap SG-1. When this breakdown potential is reached, the total voltage and energy of capacitor C8 appears on the primary winding of ignition transformer T2. This winding may be either one or two turns, depending on the spark gap used, one turn for a 470 volt gap and two turns for an 800 volt gap.

The ignition transformer is a special high frequency design with a 64 turn secondary of 8 gauge wire. The application of capacitor C8 to the primary winding generates in the secondary winding a pulse of approximately one microsecond in duration and over 25,000 volts in magnitude.

This 25,000 volt pulse ionizes the xenon gas in the lamp rendering it conductive. Capacitor C4 now has a discharge path through the lamp. This energy discharge results in the initial heating of the lamp electrodes. Resistor R45 is used to lengthen the discharge time of C14. The voltage across C14 finally falls to a voltage where diode D10 is no longer reversed biased and capacitors C2 and 3 are allowed to continue the discharge through the lamp. This continued energy discharge results in sufficient heating of the lamp electrodes to the point where the lamp can sustain an arc at its normal operating voltage of from 18 to 24 volts.

The pass transistors of the regulator are still turned on hard at this time and will continue to be until the current through resistor R21 and thus the lamp reaches a level of approximately 42 amperes. At this point, because of the biasing of the regulator's differential amplifier, the increasing lamp current is sensed and the drive to the pass regulator is reduced to maintain this maximum lamp current.

Once the lamp is lit the +400 volt supply is loaded down and the voltage across C8 may not build up to the high level necessary to breakdown the spark gap. Should, however, the lamp extinguish, the light will automatically resume the starting sequence and will continue to do so until either the lamp starts or the control voltage is removed.

To turn the light off, one need not interrupt the heavy lamp current but only disconnect the short across the control jack, thus removing power to the [multivibrator] converter and the [feedback circuit].

3.22 REFLECTOR/LAMP SEAL

The repair objective of Arc Light I was its return to Operations with minimal repacking. With the successful rejuvenation of the circuitry, using the test lamp, attention turned to the conductivity problem in the sealed, reflector mounted lamp. It was projected that considerable time and money would be saved by eradicating this conduction path, as opposed to mounting another lamp.

3.221 Hypothesis for Epoxy Conduction

A multitude of continuity checks isolated the bothersome conduction path to the epoxy, with a resistance of 100K ohms. Epoxies, however, are typically good insulators. The measurable conductivity was attributed to either humidity concentration providing a surface path of conductance, or to metallic impurities in the supposedly 100% plastic epoxy. These speculations were investigated by drying the reflector assembly in a dehumidifying oven, thus eliminating an unknown. Immediately after drying, the resistance in question was significantly higher, approaching infinity. As the reflector cooled in the lab atmosphere, the resistance steadily dropped, eventually stabilizing at its original level. The conductivity was attributed to moisture rather than metal particles.

3.222 Removal of Silicone RTV, and Epoxy

The surface layer of epoxy was physically removed with a belt sander to open the conductance path. Unfortunately, this gave no measurable increase in resistance. Alternate conduction paths were considered. For instance, a sloppy application of RTV silicone sealed the ceramic cement of the assembly from seawater. This was removed to eliminate the possibility of trapped water pockets. The unit was oven dried and resealed with a thin, uniform layer of RTV, but to no avail. The last possible path of conduction was along the quartz lamp arm. The epoxy was entirely removed by use of a solvent. Anode to reflector resistance became satisfactorily high. The lamp was reinserted in the circuitry on the test bench and shined brightly.

3.223 Thwarted Repair

The light was reassembled and filled with oil for test tank operation. Once submerged, it initially ignited and functioned at its rated current of 43 amps until power was removed. The light was allowed to cool and power was again applied, but it would not ignite. A moisture intrusion path evidently still existed. This was verified by oven drying the reflector assembly, submerging the unit, and observing that it could again be ignited only once.

3.224 Proper Material Selection

Research into the nature of the sealants in the reflector was conducted. The ceramic cement was known to be porous, necessitating the RTV seal. The RTV then was discovered to be water resistant yet not waterproof, i.e., porous when submerged. The RTV was removed. A high temperature non-metallic epoxy was located and applied as a watertight barrier over the ceramic in the base of the reflector. A thin covering of RTV was applied over the epoxy as a heat barrier. New epoxy also sealed the ceramic where the lamp protrudes through the reflector, the place where the original epoxy had been removed, but did not extend to the contact. The unit was reassembled, submerged and could successfully reignite indefinitely.

3.225 Slit in the Reflector Base

The light was left running for an extended time test. Within 15 minutes, the liquid and smoky vapor bubbles appeared, emanating from the reflector base. The substance had a malodorous, burnt aroma but could not be positively identified. It was thought to be either burned RTV, melted epoxy, or silicon oil, although no known path existed for the oil to escape. Again, the RTV was removed, and exposed an intact layer of epoxy.

The reflector was examined under high magnification. A minute hairline slit was spotted in the reflector base, in which the underlying ceramic was visible. The slit was uniform and straight, indicating it was incurred during assembly, and not due to failure in the material from heat expansion. This opening allowed oil to circumvent the epoxy seals and escape to seawater, where the heat of the lamp caused vaporization. It was known by working with the reflector that the ceramic cement had lost its adhesion to the quartz arm and acted merely as a precision spacer, thus providing a more than adequate channel for oil seepage. The solution to this problem was more epoxy, enough to cover the slitted portion of the oil side of the reflector. This solution proved successful as the light would operate cleanly for extended lengths of time.

3.23 GAS BUBBLE CREATION AT THE LAMP

3.231 Discovery and Effect

The clean running lamp allowed the observation of a physical phenomenon previously unnoticed. Gaseous bubbles were forming on the bulbous portion of the lamp. The extreme temperature at the bulb, it was deduced, drove the gas out of soultion in the water. This observation shed light on a previously unexplained occurrence, the snapping of a lamp in operation. The attitude of a light in operation is approximately 30° below horizontal. The base of the ellipsoidal reflector, being the high point, thus created a pocket in which the gas would collect. The gas, of course, displaced cooling water from that area, and created a sharp heat gradient of sufficient severity to snap the lamp arm. The snap did in fact occur at the base of the reflector.

3.232 Proposed Solutions and Actual Implementation

Reconciled to the fact that gas would continually be released, an escape path had to be created. The most direct path was simply out the reflector; however, this would unacceptably limit the orientation of the lamp to horizontal or above. A small hole was introduced at the base of the reflector, into which a fitting was mechanically attached and sealed with epoxy. The fitting was selected to accept a flexible, high temperature hose that was compatible with both silicon oil and seawater. The hose ran the length of the housing along the top and vented through the rear endplate. Upon testing, a bubble of gas was seen to emerge at approximately five second intervals. This path, forever open to seawater, added the benefit of flow through, and thus better, cooling water circulation than had previously been the case. The temperature of the water as it exited the endplate at a noticeable flow rate measured as high as 65°C.

3.24 FINAL PRODUCT TESTING

The light was operating without apparent problems at this point. A series of comprehensive tests were conducted to verify this contention. The tests included short and long interval operations, with the light under close scrutiny.

3.241 Power Up and Down, Short Interval

The short interval tests consisted of ten two minute power ups separated by two minute cool down periods. The operation went smoothly.

3.242 Power Up and Down, Long Interval

Five tests of three hours in duration comprised the long interval runs. Four major parameters were observed during this test period.

1. The current drain on the battery source was the desired 40 amps.
2. The epoxy and other seals were effective, as no oil leakage occurred.
3. Gas bubbles streamed from the unit at a consistent and sufficient rate to indicate resolution of the previous problem.
4. Oil expansion due to heat stabilized within the normal operating range of the pressure compensating diaphragm.

Having successfully passed all test criteria, the lamp was turned over to the Submersible Operations division at Harbor Branch Foundation, Inc.

4.0 DESIGN & FABRICATION OF ARC LIGHT II

4.1 CRITERIA AND GENERAL PERSPECTIVE

The arc light project schedule called for the return of a functional Arc Light I to Operations with minimal repacking. The option of basic design improvements and refinements was reserved for Arc Light II. Experience obtained in repairing the prototype Arc Light I indicated several areas in need of design modification. Inherent problems, reliability, ease of handling and repair, and versatility were considered in establishing new requirements, i.e. a revised criteria. These are:

1. Avoid gas bubble entrapment.
2. Avoid custom modified components for pressure compensation.
3. Provide ready access to circuits.
4. Provide quick and easy lamp replacement.
5. Provide improved ruggedness and increased reliability of physical component mounting.
6. Provide adjustable field of illumination.

4.2 MECHANICAL DESIGN

A primary reason for repackaging Arc Light II was to rectify the problems associated with the prototype unit's reflector and lamp assembly, i.e., conductivity, gas trapping, non-adjustability, high temperature seals, and serviceability.

Thus the focus of attention for design revolved about the lamp, with subsequent details following.

4.21 REFLECTOR AND LAMP MOUNT DESIGN

The lamp would remain in seawater for cooling purposes. The contacts of standard model lamps, which must of course be isolated from seawater, were cylinders half again the diameter of the quartz arm. This arrangement severely complicated the desire for a plug in mating. The manufacturer was consulted and agreed to customize the lamps, such that the 11/16" diameter quartz arm abruptly tapers to an 1/8" diameter contact pin, extending 3/4" beyond the quartz.

4.211 Easy Lamp Replacement

For reasons explained later, the electronic components were contained in a one atmosphere pressure housing. The lamp, therefore, could no longer penetrate the housing, lest it be subject to the pressure gradient. The design, see figure 2, called for a silica bronze rod in which was machined a 3/4" long concentric sleeving to accept the contact, which extends through the bulkhead to the circuitry. O-rings provided the pressure seal, while Delrin insulation assured the electrical neutrality of the housing. Delrin specifications were obtained from a Cadillac Plastics data bulletin. The melting point lists at 175°C, well above anticipated temperatures.

The total dielectric strength for the minimum thickness of delrin used, 0.089", was greater than 52,000 volts. This figure was determined by conservatively extrapolating a non linear curve, with a resulting correlation coefficient R = .971. This thickness represents the isolation between the bronze rod and penetration opening in the aluminum bulkhead.

4.212 Pressure Compensation for the Lamp

Uniform pressure over the bulb was achieved by designing a toroidal piston, with a 1/4" O-ring in its inner diameter, to slide over the quartz arm. The cavity beneath the piston was oil filled for electrical isolation. The piston was contained in a ring machined into the bulkhead. To ensure the piston travel remains at a minimum, the expansion of oil due to heat was determined. The volume of oil in this cavity was estimated from accurate drawings, and doubled to account for crevices and to thereby assure a conservative estimation. This yielded a total of 0.90 cu. in. The rated expansion of Dow Corning 200 is 0.13%/°C. The extremely unlikely occurrence of a 200°C temperature rise during operation was considered. Such an occurrence would increase the total oil volume by 0.23 cu. in. For the piston surface area of 2.82 sq. in., a linear movement of 0.082" would be realized. The piston could sustain a linear movement of 0.31 inches, providing more than adequate head room.

4.213 Adjustable Reflector Mounting

The design of the cathode connection called for a molded neoprene rubber cap, containing a bronze concentric sleeved connector attached by wire to a penetrator, and to the printed circuit board. Prior to attachment, the cap would be oil filled. The lamp would thus be fully supported independent of the reflector. For total flexibility, the reflector was attached by the outer edge lip to six threaded standoffs. Focusing would occur by adjusting the reflector relative to the fixed lamp in use. The option of quickly and easily attaching alternate reflectors would thus be available. In addition to better cooling, the collection of gas bubbles was circumvented by this design, as the entire reflector, suspended in seawater, would be open at either end.

4.22 ONE ATMOSPHERE OIL FILLED PRESSURE HOUSING

The pressure compensating design of Arc Light I required that all power transistors and electrolytical capacitors be custom modified. The transistors had minute holes drilled in the casing to prevent crushing. The holes also opened the door to impurities. Flexible caps were affixed to the opened ends of the fluid filled capacitors. This arrangement was subject to leakage, as well as being a time consuming process. Weighed against these undesirable features were the benefits of submergence in oil. The oil provided quicker and far more effective component cooling than air, by transferring heat to the housing through convection currents. In addition, by being a good dielectric, it effectively suppressed any tendency towards internal arcing. The component housing design for Arc Light II was thus optimized by use of an oil filled, one atmosphere, pressure vessel. A small internal air space was included, to allow for oil expansion with heat. A pressure relief valve was also called for, as an added safety precaution.

4.221 Mechanical Support of Printed Circuit Boards

To minimize the quantity of discrete mechanical parts, several multi-function items were incorporated in the design. The silica bronze rod provided the electrical path to the anode, supported the printed circuit boards mechanically, and was simultaneously involved in the housing's closing and sealing. The threaded bronze rod was inserted through the aluminum bulkhead, electrically isolated by delrin washers and sheathings, and bolted from the inside. A flange was provided to prevent pull-through. A 3/4" delrin tube separates the two printed circuit boards, and insulates this voltage spike and current carrying rod. The threaded rod extends one inch beyond the second nut. An external knob on the aft endbell mates the bronze with an affixed, non-conductive, delrin extension rod. The unit is thus securely closed, and the slight rod tensioning reinforces support for the printed circuit boards.

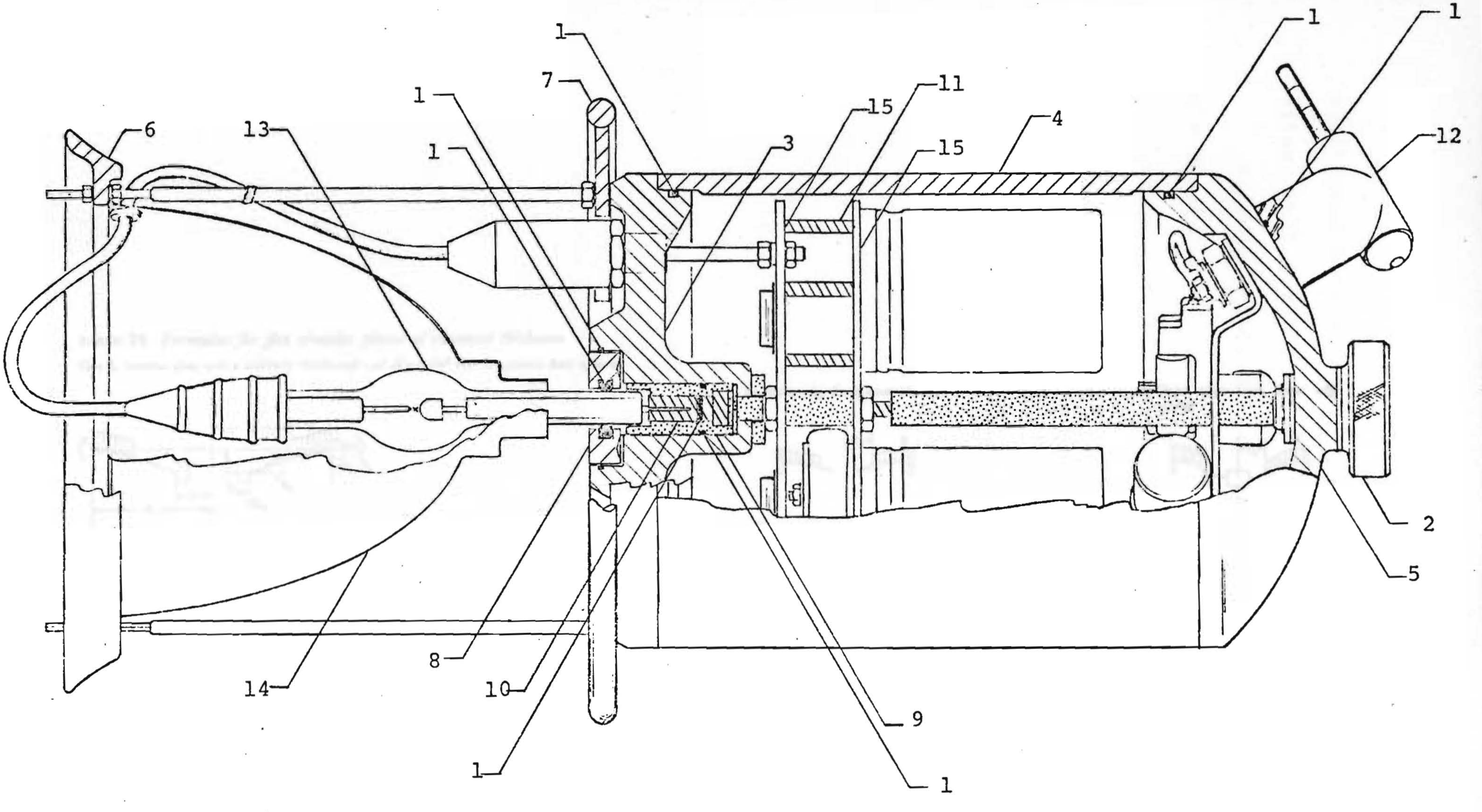
4.222 Endbell Designs

The depth requirement for all JSL equipment is 3,000 feet, where the ambient pressure is 1336 psi. Aside from a sphere a cylinder is the most efficient shape for a pressure vessel.

From a previous project, drawings existed for an aft endbell that, with minor modification, was perfectly applicable to the arc light. The endbell was designed to fit a stock tubing that had an outer diameter slightly larger than the reflector, and included the external knob used to assemble the final unit.

Available material, machining difficulties, and design requirements such as a flat bottomed piston receptacle were considered in choosing the flat plate design for the forward endbell, see figure 4. A strength of materials analysis was conducted to determine the necessary plate thickness. Effort was made to maximize plate continuity. The resulting design is an 8.65" diameter, .75" thick plate with a centered .937" bored cavity. Two concentric rings extend externally from the plate. One ring is the piston guide and the other is drilled and tapped for the reflector standoffs. The base of the lamp receiving cavity abruptly reduced to a diameter of .438", at a thickness of .25" for penetration of the bronze conducting rod.

The required plate thickness was determined by application of appropriate formuli from Formulas for Stress and Strain, by Roark and Young. Model 2f, from "Table 24: Formulas for flat circular plates of constant thickness," on page 340, see figure 5, was chosen to represent the arc light endbell, as its restraints are outer edge fixed, inner edge guided. The cylinder forming the lamp receptacle on the endbell functions as an inner edge guide, whereas the combined effect of

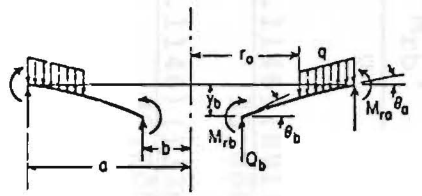


1.	O-Ring Seals	6.	Aluminum Guard Ring	11.	Bronze Interconnect Standoffs
2.	Closing Knob	7.	Aluminum Handling Ring	12.	Power Penetrator
3.	Aluminum Fore Endbell	8.	Aluminum Piston	13.	Arc Lamp
4.	Aluminum Housing Tube	9.	Delrin Insulators and Spacers	14.	Reflector
5.	Aluminum Aft Endbell	10.	Bronze Current Carrying and Central Support Rod	15.	Printed Circuit Boards

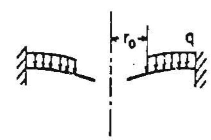
Figure 4: Arc Light II Assembly Layout

TABLE 24 *Formulas for flat circular plates of constant thickness*

Case 2. Annular plate with a uniformly distributed load of q lb/in² over the portion from r_o to a



2e. Outer edge fixed, inner edge free



2f. Outer edge fixed, inner edge guided

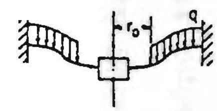


Figure 5: Analytical Models for the Forward Endbell of Arc Light II, from Formulas for Stress and Strain by Roark and Young, Chapter 10

additional material and restraint by the housing tube effectively fix the outer edge.

Bending stresses are generally expressed as $\sigma = 6M/t^2$.

$M = K_M q a^2$

where ν = poissons ratio, assumed = .3

t = thickness = unknown

σ = maximum material yield stress = 35,000 psi

K_M = a constant, that for this case = $K_{M_{rb}}$

where r refers to radial direction evaluation and b refers to inner edge evaluation.

q = load per unit area = 1336 psi @ 3,000 ft.

= 891 psi @ 2,000 ft.

a = radius of the plate = 4.315"

r_o = radius to the load = .469"

b = radius to the inner edge, where in this case b =.469"

For the case where $r_o = b$, calculations are simplified by use of the table for model 2f that yields $K_{M_{rb}} = 0.1146$. Substituting for M in the general bending stress equation, and solving for t, yields:

$$t = \left(\frac{6M}{\sigma}\right)^{\frac{1}{2}} = \left(\frac{6K_{M_{rb}} q a^2}{\sigma}\right)^{\frac{1}{2}}$$

thus

$$t_{2000\ ft} = \left(\frac{6(0.1146)(891)(4.315)^2}{35{,}000}\right)^{\frac{1}{2}} = 0.57"$$

and $$t_{3000\ ft} = \left(\frac{6(0.1146)(1336)(4.315)^2}{35{,}000}\right)^{\frac{1}{2}} = 0.70"$$

The factor of safety for the actual plate thickness of .75" is 1.1 at 3,000 feet, and 1.32 at the maximum working depth of 2,000 feet. These margins were deemed acceptable.

A similar analysis was conducted for the machined plate at the base of the lamp cavity. This plate is represented by Model 2e: Outer edge fixed, inner edge free. Here,

$$r_o = b = 0.125"$$

$$a = 0.469"$$

$$b/a = .125/.469 = .267 = .3$$

$$\rightarrow K_{M_{ra}} = 0.1135$$

where r refers to radial direction evaluation and a refers to outer edge evaluation

$$\sigma = 35{,}000 \text{ psi}$$

$$q = 1336 \text{ psi @ } 3{,}000 \text{ ft.}$$

$$t = \left(\frac{6M}{\sigma}\right)^{1/2} = \left(\frac{6K_{M_{ra}} q a^2}{\sigma}\right)^{1/2}$$

$$t_{3{,}000\text{ ft}} = \left(\frac{6(.1135)(1336)(.469)^2}{35{,}000}\right)^{1/2} = .08"$$

The actual 0.25" material results in a safety factor of 3.3 at 3,000 foot depths.

4.3 ELECTRICAL DESIGN

4.31 PURPOSE: DURABILITY AND SERVICEABILITY

The purpose of redesigning the electronic packaging was two-fold; durability and serviceability. More than one occurrence of bent and shorted leads was discovered in the repair of Arc Light I. Coupling this with the inaccessibility of the circuit to probes and inspection, a redesign of the layout was warranted.

Application of printed circuit board technology provided the simplest, most practical design solution. Advantages accrued by printed circuit board usage include:

1. Circuit modularization for ease of replacement.
2. Exceptional reliability of mechanical mounting.
3. Direct and easy access to circuit nodes for testing and repair.
4. Near elimination of interconnecting wiring.
5. A smaller, more compact unit over all, due to denser packing.

Selection of the printed circuit board material involved the following basic criteria:

1. Capability to safely carry the current and voltage levels of the arc light without overheating, arcing or deteriorating in any way.
2. Sufficient mechanical strength to support all components including heavy items such as electrolytic capacitors and transformers.
3. Mechanical and electrical stability at high temperature.

4.32 PRINTED CIRCUIT BOARD COPPER THICKNESS AND WIDTH OF CONDUCTIVE PATH

Consultation with printed circuit board manufacturers provided the necessary information for proper board selection. The copper available in laminate thickness is specified in ounces per square foot, available from one to ten ounces, where one and two ounce copper are standard. Available copper etching capabilities, however, limited the selection of copper thickness to five ounces or less. The laminates are available in overall thicknesses from 0.003 to 6 inches. The primary restriction in choosing any conductor size, wire and printed circuit board, is temperature. The design power rating for the arc light is 1060 watts, with 45 amps current at the lamp voltage of 23.5. As a reference, the cross-sectional area of #10 American Wire Gauge (AWG) solid wire, rated for 55 amps, is 0.008155 in^2. To achieve the comparable wire area on a 5-oz. copper p.c. board requires a 1.165" wide conductor path. It has been established that, in general, the flow of current takes place along the outer surface of a conductor. The surface area of the 5-oz. copper printed circuit board conductor path is seven times greater than that of #10 AWG wire, indicating a reduction in conductor width was reasonable. Figure 29, page 1-52 of the Handbook of Electronic Packaging by Charles Harper indicates temperature rise versus current for 3-oz. copper. Extrapolating the 40°C rise curve to a current of 45 amps gives a minimum conductor width of 0.36 inches. The selected 5-oz. copper thickness provides 66% more copper for better heat transfer than 3-oz. copper. The minimum conductor width for high current paths was set at 0.45", providing 25% greater conductor width than is required. Combined, the printed circuit board design results in almost a two to one safety margin.

4.33 MATERIAL SELECTION, TEMPERATURE AND STRENGTH CONSIDERATIONS

The modified epoxy glass laminate board material was selected for its excellent physical specifications. These include a continuous operating temperature of 200°C and flexural strength of 75,000 psi at room temperature and 15,000 psi at high temperature. The overall board thickness is 1/8 inch, for rigidity. The dielectric strength, indicating the material's breakdown voltage, is rated at 800 volts per mil. For this reason, a minimum insulation width of 0.10" was specified, establishing a breakdown (i.e., arcing) voltage of 80,000 volts for the circuit.

4.34 COMPONENT PLACEMENT CONSIDERATIONS

The following guidelines were established for the physical layout of the printed circuit board:

1. Minimize high current conductor lengths.
2. Maximize space usage with a minimum number of boards.
3. Minimize and simplify board interconnects.
4. Provide for adequate heat dissipation.

Physical space requirements permitted the use of only two boards to contain every electronic part, except for fuses and the noise abating capacitor filter, which are located within the hemispherical endbell. Within each board, components were systematically arranged according to their functional group. The current amplifier, feedback circuit and majority of the starting circuit were on the board nearest the lamp. The second board contained larger components of the starting circuit. The copper circuitry of the boards face each other, allowing eight brass standoffs to provide both mechanical support and electrical interboard connection. Current flows to the lamp through the quarter inch central support rod, and returns through an extended penetrator pin that directly bolts to the board nearest the lamp. A jumper wire in the circuit provides for the addition of a low current on/off switch at a later date if required. Such a feature was deemed unnecessary in Arc Light II at the time of design. The only hard wire in the unit, aside from the jumper, are the main power leads extending from the fuses to the adjacent printed circuit board. This feature provides the necessary flexibility to access the housing. The physical isolation of all circuitry from the housing assures its electrical neutrality, a JSL requirement, save for the remote possiblity of a leaky penetrator. Heat dissipation is accomplished by providing large copper pads on the component side of the boards, on which the electrically isolated components are mounted. Convection currents are established in the oil, whereby heat is transferred through the housing to the sea.

5.0 CONCLUSION

The arc light project as a whole has been a long term proposition, having involved, to date, the attention of five separate individuals or teams, for one reason or another. Most recently Arc Light I was analyzed and redocumented, repaired, and returned to Operations. Repair was sound in execution, but of a temporary nature. The unacceptability of this state of affairs triggered the immediate execution of a total repackaging and rebuilding of Arc Light II.

The design of Arc Light II, designated to replace Arc Light I, circumvents the problems associated with the prototype unit. It is currently in fabrication, and is fully expected to meet all design criteria, resulting in a flexible, easy to access, and reliable arc light system.

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