

ARC DISCHARGE CONVECTION STUDIES: A SPACE SHUTTLE EXPERIMENT

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ABSTRACT

Gravity plays a significant role in many products, operations and processes, but for many complex systems it is often difficult to separate the effects of gravity from those of other forces and influences. In this experiment aboard Shuttle it was possible to test and examine the gravity-free performance of high intensity discharge lamps. Construction of the experimental payload required careful integration of the structural, electrical and optical systems. Thermal balance and automatic control of the experiment were major issues. The data are expected to yield detailed information concerning the distribution of radiating species in the arc. The distributions are strongly affected by gravity and are the subject of intensive theoretical modeling efforts. The Shuttle data provide unique input to these activities aimed at the development of improved light sources.

INTRODUCTION

A research team at GTE tested three arc discharge Metalarc® lamps in the microgravity environment of one of NASA's small self-contained payloads during the February flight of STS-41B. The project was jointly sponsored by GTE Laboratories, the corporate research facility, and GTE Lighting Products, the manufacturer of Sylvania lamps. The experiment was performed on high intensity metal halide lamps and included the collection of performance data and photography of the arc.

When operated on earth, gravity induces circulation of the hot gases in these arc lamps. That circulation, or convection, affects the electrical and light-producing properties of the arc. These effects, mixed with others, are difficult to separate in ground-based experiments. The observations made while gravity was "switched off" provide verification of theories of arc behavior, clarify the roles of convection versus other processes in the arc, and may lead to potential product improvements that result from altering the influence of convection.

In metal halide lamps an arc is established in an inner capsule, or arc tube, which has metal electrodes protruding through its ends to pass electrical current through the gas inside. The gas is mostly mercury vapor with small

amounts of sodium and scandium added to improve the color of the radiated light. During normal operation convection results in segregation of the various species, an effect which impacts the color and efficiency of the light source.

In the Shuttle experiment various properties of the arc were observed with the complication of convection removed. The arcs were photographed to record their general structure and, by means of three bandpass filters, to record the emission from mercury, sodium and scandium. In addition, a record was made of arc current, arc voltage, relative light intensity and arc tube wall temperature.

GENERAL DESCRIPTION OF THE PAYLOAD

The payload, shown in Figure 1, included three separate but identical experimental systems. Three experiments were included for checking repeatability of lamp performance and for redundancy in case of partial failure. There were three lamps symmetrically arranged under the top plate. Each lamp had four mirrors surrounding it to provide multiple filtered images including a white light image. Three 35 mm cameras with extended backs for 250 exposures recorded all images and digital data. A portion of each camera's field of view included a bank of digital LEDs which displayed various operating parameters. Each photograph was, therefore, a composite of these data and the four images of the respective lamp under test. (See Figure 3.)

The power source for both the lamps and the master control circuits was a collection of nineteen battery packs with a total rating of about 4 kWhr. A plug-in card rack contained the three electronic control circuits and electronic inverter/ballasts. The sealed container was filled with 1 atmosphere of dry nitrogen which was maintained throughout the flight.

Each experiment was initiated by an astronaut closing a relay. This closure started the control circuit which, among other things, sent pulses to the camera for taking pictures at intervals of seven seconds. The control circuit also turned on power to the lamp. Typically these lamps take five to eight minutes to warm up and stabilize. Since each experiment duration was 30 minutes, the lamp reached equilibrium well before the experiment was completed.

STRUCTURAL SYSTEM

The cover plate supplied by NASA had 45 tapped holes and could not be modified. The lamps with their mirrors and filters were attached directly to the cover for optimal heat transfer. Three columns at 120° intervals were also attached to this plate at the outer perimeter with three screws each. The columns, about 10 inches long, supported a full diameter shelf. The three cameras as well as the digital display panels were attached to this shelf. Three additional columns, about 13 inches long, were attached to the opposite side of this plate and supported a second shelf. A card rack for plug-in printed circuit boards was located between the two shelves. A non-metallic battery compartment was integrally attached to the far side of the second shelf.

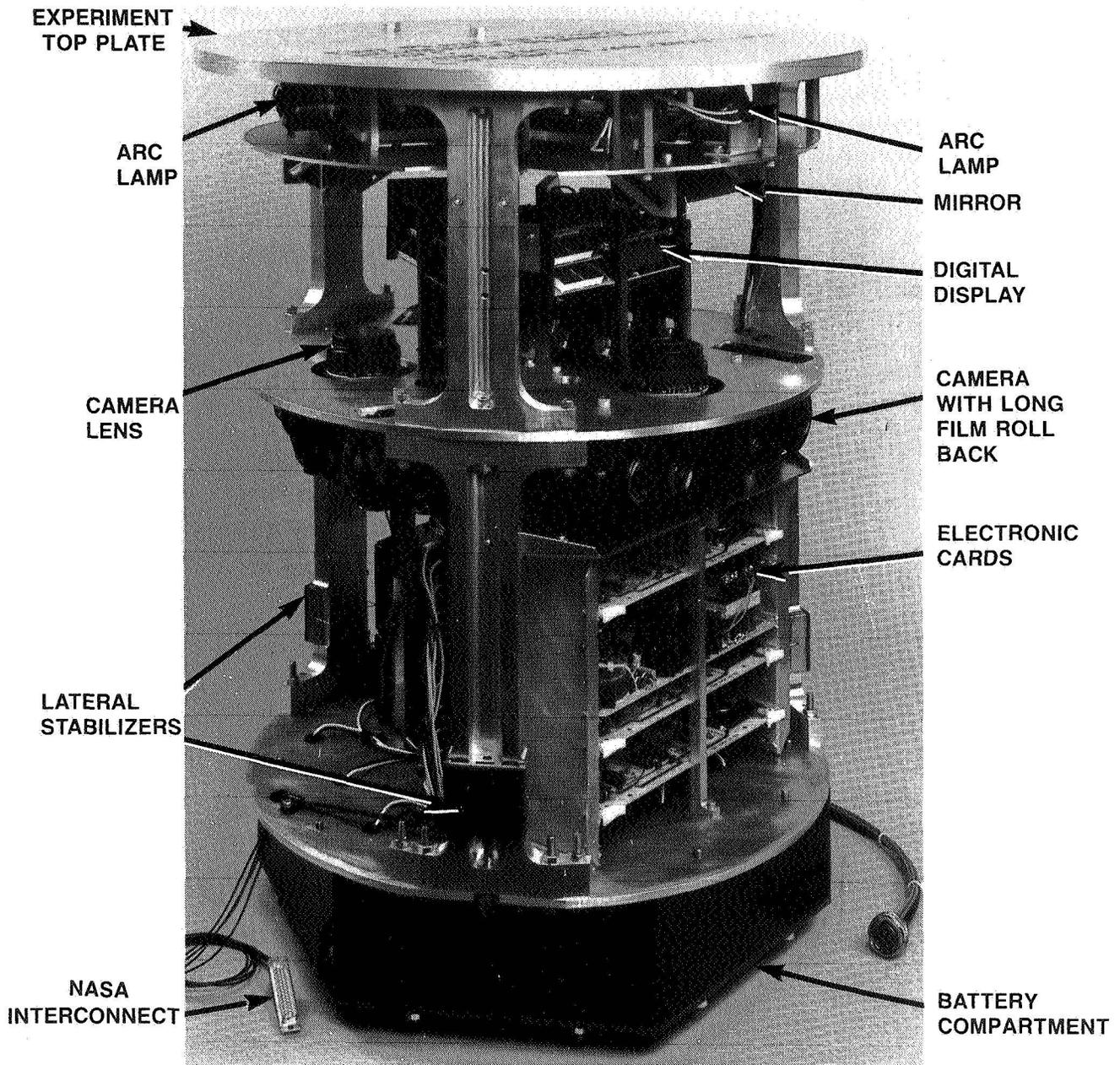


Figure 1: The Payload for the Metal Halide Lamp Experiment.

Three adjustable lateral support pads, shown in Figure 2, were mounted on the three lower columns in line with the center of gravity of the suspended payload. Thus, the inertial forces generated during transverse oscillation were largely transferred through the pads to the wall of the container. These pads were adjustable from the open bottom of the container by means of a jack screw which translated a ramp under the pad. This design was quite simple and compact and permitted location of the lateral support pads at any arbitrary position along the payload to line up with the CG if desirable.

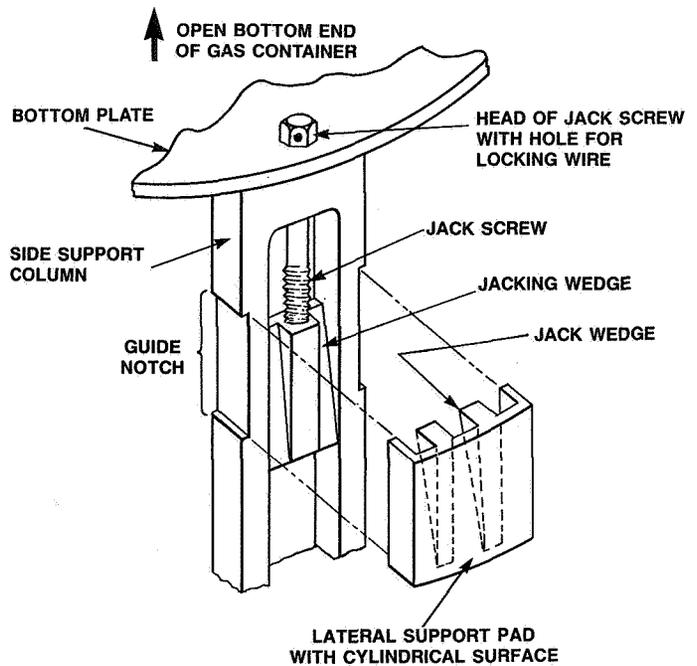


Figure 2: Detail of the Lateral Support Pad.

PHOTOGRAPHIC AND OPTICAL SYSTEM

The only instruments of data collection used in this payload were Nikon F3 cameras. The cameras were equipped with alkaline battery powered motor drives, and were outfitted with extended backs which accommodated 38 foot rolls of film for over 250 exposures. By including the digital display of

measured data in the cameras' field of view the overall problem of data collection and synchronization was greatly simplified, and any doubt about the relationship in time between the arc photographs and other data being monitored was eliminated. Since each frame on the film contains a complete instantaneous record of data, coordination of the analysis is simplified.

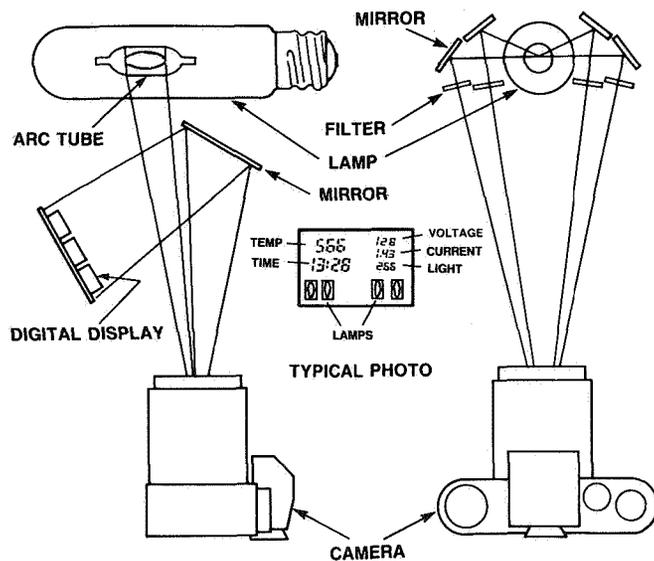


Figure 3: Two views of the Photographic Optical System.

The camera was tripped once every seven seconds so that 256 exposures were made during the 30 minute test. As shown in Figure 3, each lamp was outfitted with four mirrors to provide four virtual images falling on a common plane for sharp focusing. Each of these

images was covered with a different narrow band filter to isolate mercury, sodium and scandium radiators in the arc. The fourth filter was of neutral density to adjust the white light image for equivalent exposure. All mirrors used in this assembly were front surface, and some had selective coatings designed to reduce the energy which must be absorbed by the filters.

The six channels of data being displayed on the digital panel were projected to the camera by another larger mirror. Lamp voltage, lamp current and photopic light output were displayed on digital voltmeters. (Photopic light characterizes the spectral response of the human cone receptors. It was simulated with a photopic absorption filter in front of the photodetector.) During DC operation the lamp voltage polarity was indicated by a plus or minus sign on the display. A digital thermocouple meter displayed temperature of the arc tube as detected by a chromel/alumel thermocouple. A clock was installed to display elapsed time starting with zero at the moment of startup. All displays used LEDs for uniform photographic brightness throughout the experiment. The LEDs were blanked between camera exposures to conserve power. They were also held in the fixed-display mode during exposure so that changes in digital reading were not ambivalently recorded by the camera.

The film used was Kodak Technical Pan 2415, a universal film on a highly stable Estar base which can be developed in a variety of ways for different speeds and contrasts. The selected processing resulted in a very long and linear exposure range which could accommodate the wide brightness range encountered during startup as well as the uncertain brightness level to be attained in the microgravity environment. A photographic step wedge was pre-exposed on the film for calibration of density measurements of the arc images. This wedge was included on a blank strip at the head of the film and at periodic intervals throughout the film. To prevent the calamity of losing an entire roll of film during processing, the film was cut into five foot lengths and developed separately in conventional developing tanks. The developing process was controlled as closely as possible to keep all sections at similar density, but the local step wedges serve as a final reference for the precise density.

ELECTRICAL SYSTEM

The power source for this payload was a set of alkaline manganese dioxide cells connected in a series/parallel configuration. The cell used was a size F, manufactured by both Duracell and Union Carbide, and is available in multiples incorporated in consumer lantern batteries. This primary cell has an excellent performance record, very long storage life, moderately high energy density, good low temperature performance and low cost. At high discharge rates it has a sloping discharge, and since it is non-rechargeable, additional sets of batteries were required during pre-flight testing. The cell is vented to eliminate the potential for an explosion. During short circuit tests of single cells, the temperature rose about 70°C, but no noticeable release of gas or slurry was observed. Temperature rise during the normal discharge rate of under 2 amperes was about 2°C.

The battery construction, shown in Figure 4, uses seven cells in series, and a 7-ampere fuse. The fuse was located between cell numbers 2 and 3 so that

not more than one cell could be included in a case-to-case short without including the fuse. Four of these battery packs were connected in series to develop the required voltage, and four such series strings were connected in parallel, using diodes, to supply the required current. Three separate 7-cell batteries were used individually for powering the timing control circuits. These latter cells were respectively switched on by the relays in the NASA Control Decoder to initiate each experiment. The 19 batteries were installed hexagonally close-packed in the hexagonal battery compartment with their leads passing straight through individual grommets holes in the lower shelf.

The schedule of the experiment was designed to simplify design and operation of the timing circuit. All events occurred at simple geometric multiples of the seven second camera cycle. At the 15 minute point (128 x 7 sec) the lamp power switched from 60 Hz square wave to DC. The DC polarity was reversed every 112 seconds (16 x 7 sec). An optional function was to modify power levels at intervals of 7.5 minutes (64 x 7 sec.). The entire experiment was completed in 30 minutes (256 x 7 sec) at which time all power was turned off.

This mode of operation permitted the use of a simple circuit consisting of a clock set for 7-second pulses, a counter with outputs at geometric multiples of the 7-second input pulse and various gates and buffers for outputs. Simplification helped to maintain a high level of reliability.

Discharge lamps require a series ballast to limit the current after the arc is established. Ballasts for AC operation are typically inductors. This experiment required DC to AC inversion, high voltage starting pulses to guarantee startup and current-limiting during DC operation. An electronic ballast circuit was designed which incorporated all these functions. This circuit utilized a commercial CMOS regulating pulse width modulator and specially designed inductors. The regulation was excellent with less than 1% variation in current for a DC supply voltage ranging from 43 down to 22 volts.

The lamp under test was a standard 175-watt Metalarc® lamp manufactured by GTE with a slightly modified fill. It was mounted in a slender evacuated outer jacket to minimize the size of the optical system with its four mirrors and filters. It operated at 135 volts and drew 1.3 amperes. The outer jacket of the lamp was supported at each end in a V-block type cradle with a spring to secure it in place. This arrangement was designed to minimize stress on the jacket thereby reducing the chance of breakage.

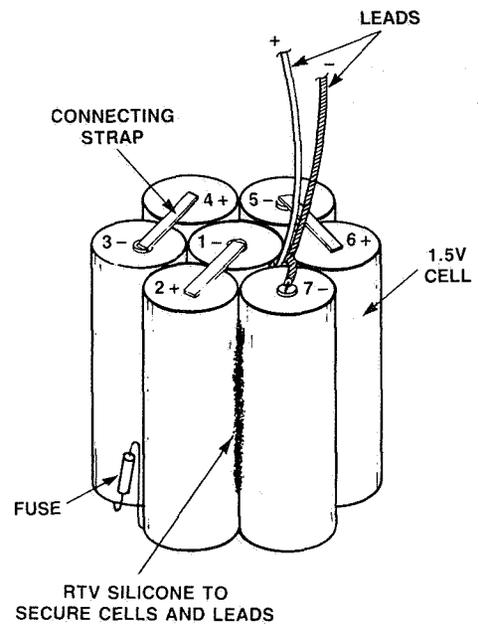


Figure 4: Detail of the 7-Cell Battery Pack.

THERMAL CONSIDERATIONS

The first Get Away Special payload flown on Shuttle was an instrumented package made by NASA for gathering information about the container design itself. A number of temperature curves were obtained from this payload. Although the external portions of the container experienced wide excursions in temperature as the shuttle changed its orientation relative to the sun and the dark sky, the internal temperatures remained relatively stable. The instrument plate, the battery box and the tape recorder all rose a few degrees upon takeoff to about 30°C then slowly cooled about 5°C per day. This experimental payload also had some heat dissipated into the top mounting plate at three different times during the flight. These dissipations were 160, 330 and 320 watt-hours respectively. The plate heated about 10°C at most while other components experienced very little temperature rise.

Since our payload was to dissipate only about 100 watt-hours on three different occasions with many hours between them, heat rise problems did not appear to be severe. Calculations indicated that even if all the energy from the lamp was absorbed by the end plate, the temperature rise would be about 33°C. If this heat were to distribute uniformly throughout the payload, with no losses, the temperature rise of the payload would be about 5°C. As a result of these expectations, it was decided to outfit our payload identically with that of the test payload, i.e., to utilize an anodized mounting plate covered with insulation. This insulation was also expected to help prevent the batteries from cooling excessively. In the hope of maintaining the batteries above 10°C, the experiments were requested to be performed as early in the flight as possible. Heat rise of the batteries during normal use was measured to be about 2°C.

Since natural convection is absent in the microgravity of orbit, small fans were provided to circulate the nitrogen atmosphere over the circuit boards. These were not only provided for the obvious sources of heat such as power transistors, but for other components such as resistors which have short thermal time constants and may have experienced considerable heat rise with little more than diffusion and point contact conduction to cool them.

The glass mirrors and filters were mounted in such a manner as to leave them free to move relative to their metal supports to prevent risk of breakage due to thermally-induced expansions of the components.

TESTING

NASA recommended a single vibration test which effectively tested for noise and acceleration. If the test were not performed, a more conservative stress calculation was required. A finite element stress analysis of the structure was performed during design of the payload. The vibration test was performed on subassemblies early in the project as well as on the completed payload. Although not required, the test was, nevertheless, performed primarily to uncover potential weaknesses which would jeopardize the success of the mission. The payload had been designed using conservative practices—low stress levels, multiple screws with locking devices, oversized

cables well supported with clamps, glass components mounted on cushions and retained with springs, etc. The payload suffered no physical damage during launch and orbit.

RESULTS AND CONCLUSIONS

The payload was retrieved within 2 weeks of the landing at Kennedy Space Center. Examination unveiled no damage to the payload and subsequent processing of the films revealed that all three systems performed nearly to perfection. The integrity of the structural system and the performance of the automatic electrical systems indicate that the basic design is sound. Modification of this design to accept various future experiments can be readily effected.

Film processing was carried out in stages to ensure that development of the analog arc images resulted in optimal data acquisition. Linear radial scanning at selected arc axis positions produces quantitative data for the mercury, sodium and scandium emissions. Determination of the radial arc temperature profile from the scanned image of mercury intensity and determination of species density distributions are in progress. These analyses require absolute calibration of film densities as a function of radiated power and complex computer aided inversions of density distribution data.

Evaluation of digital film data shows that the 175 watt Metalarc® lamp has a significant increase in light output when convection is removed in the gravity free environment of this experiment. This increase in efficacy is due to a more uniform temperature and radiating species distribution. Operation under DC power reveals sizable cathaphoretic effects that are being studied further.

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