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FOREWORD

This report was prepared for the National Aeronautics and Space Administration, Marshall Space Flight Center, as a Final report on Contract NAS8-30780, "Development of a Flow Visualization Apparatus." The work was performed in the Space Processing Group of the Huntsville Research & Engineering Center.

The NASA Contracting Officer's Representative for this task was B. S. Blake, MSFC Space Sciences Laboratory.

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SUMMARY

The effects of convection in space processing experiments involving fluids is now recognized as an important factor in the success or failure of a particular process. Research efforts and flight experiments have been performed in an attempt to understand the magnitudes and effects of low-gravity convection. Most of the existing studies which have been done are concerned with the effects of low-gravity fluid motions on thermal histories and heat transfer. There has been little effort expended on actually visualizing convective flow in a low-gravity environment. The purpose of this study was to investigate the use of an optical flow visualization device for studying convection flow patterns. The investigation considered use of a shadowgraph, schlieren and other means for visualizing the flow. A laboratory model was set up to provide data on the proper optics and photography procedures to best visualize the flow. A preliminary design of a flow visualization system is provided as a result of the study. Recommendations are given for a flight test program utilizing the flow visualization apparatus.

Section 1
INTRODUCTION

Natural convection and its effects on heat and mass transfer processes in fluids is a major concern in most space manufacturing processes. Density gradients in a fluid, induced by temperature or concentration changes, in the presence of gravity gives rise to buoyancy forces. This gravity-driven convection can be the dominant mechanism affecting fluids processing in a ground-based laboratory. One of the major advantages foreseen in manufacturing products in space concerns the reduction of this buoyancy-driven fluid flow. Moreover, the ability to control the magnitude of convection in a low-g environment offers advantages in materials processing which cannot be achieved on earth. When convection is suppressed, precise knowledge of diffusion rates of mass or heat become critical as many processes become diffusion controlled. Prediction of accurate diffusion rates by theory is often intractable. Thus, a means of measuring concentration and temperature gradients during low-g processing is very desirable.

However, it is erroneous to conclude a priori that natural convection will be totally absent in a low-g laboratory. Gravity levels of even 10^{-6} g can cause significant convection if the temperature or concentration gradients are very large. Results of experiments flown aboard Apollo 14 and 17 indicate that the low-g convection can be an important factor in determining fluid behavior and heat transfer. Changes in the magnitude and/or direction of acclerations can also be an important factor as well as convection driving mechanisms other than gravity. Accurate knowledge of the magnitude and pattern of convection is essential because many promising space manufacturing processes (i.e., fiber eutectics for optical communications, uniformly doped semiconductors, vapor grown single crystals) depend upon the elimination of natural convection. Among the processes most likely to be drastically affected by convection are various crystal growth procedures and material separation techniques such as electrophoresis and Soret methods. These phenomena must be understood and explained if any significant process of this type is to be designed for space manufacturing.

Most of the existing studies which have been done are concerned with the effects of low-gravity fluid motions on thermal histories and heat transfer. There has been little effort expended on actually visualizing convective flow in a low-gravity environment. The purpose of this study was to investigate the use of an optical flow visualization device for studying convection flow patterns. The investigation considered use of a shadowgraph, schlieren and other means for visualizing the flow. A laboratory model was set up to provide data on the proper optics and photography procedures to best visualize the flow. A preliminary design of a flow visualization system is provided. This report summarizes the results of the study and provides recommendations for a flight system to visualize convective flow in low-gravity.

Section 2
TECHNICAL DISCUSSION

2.1 TECHNIQUES REVIEW

Techniques to provide a visual observation of the convection in a confined region can be classified broadly as (1) particle methods, and (2) schlieren methods. The approach of having particles of material suspended in the fluid provides a trace of the fluid flow which can be related to streamlines. The technique would most likely not be acceptable for experiments aboard a spacecraft. The large accelerations present during the launch phase could redistribute and mix the particles such that a settling time greater than the low-g period would be required. If particle size and density were selected for minimum settling time, the problem of backscatter and electrostatic effects would still be present. This approach would also not be acceptable for visualization in a crystal growth cell.

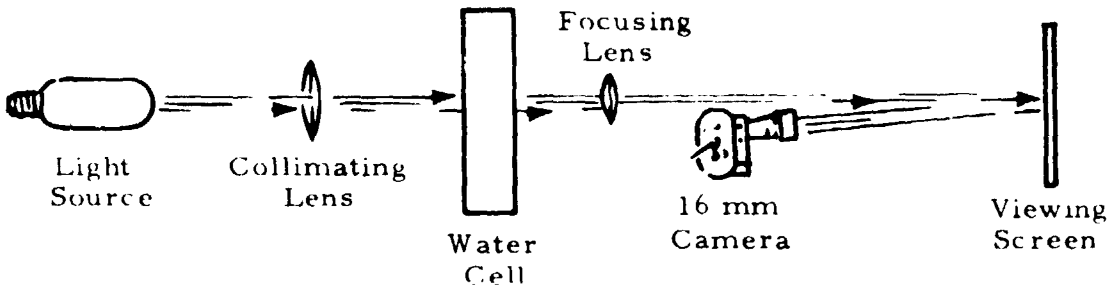
A literature search was performed for applications of flow visualization techniques to natural convection. Most of the current literature on natural convection flow visualization indicates that "particle" methods are used almost entirely. For flows of liquids, particles of various material are suspended in the fluid and photographs are taken of the particles as they move due to convection of the fluid. For flows of gases, various type of "smoke" are used to trace the streamlines due to convection. A general description of schlieren methods is given in Ref. 1. This text was reviewed and a study made of "color" schlieren techniques. This approach would be useful in terms of obtaining quantitative data. However, the critical alignment problems may prohibit its use on a spacecraft. These alignment problems were investigated and consideration was given to this technique for final design.

Reference 2 contains excellent interferometric photographs of Benard convection of water in a rectangular container. A helium-neon laser was used in the system to record density contours in a "heating-from-below" orientation. By restricting the test parameters to the range where density is a linear function of temperature, the investigators were able to obtain isotherm maps. These were compared to analytical predictions and generally good agreement was found. The interferometer technique was investigated for possible use on a spacecraft for low-g convection visualization. A good discussion of both the schlieren and shadowgraph methods is given by Weinberg (Ref. 3). However his application was for a study of flames and not natural convection. Baker (Ref. 4) presents a technique for measuring fluid velocities in low speed flows. The technique uses a pH indicator and is applicable in aqueous solutions. A solution of "thymol blue" is used in conjunction with an electric current to detect changes in color of the solution. These color streaks provide a measure of the flow velocity.

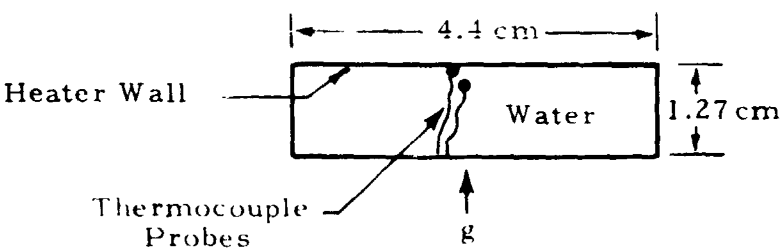
The technique chosen for this study consists of using a schlieren or a shadowgraph approach. A light source, collimated by an appropriate lens, passes through the test cell. The changes in illumination of the light as it passes through the fluid provides a measure of the density changes in the fluid. These can be focused onto a viewing screen and will appear as different shades of gray. The technique is referred to as a simple shadowgraph and actually provides a measure of density gradient gradients. By using an appropriate knife edge at the focal point to block a portion of the light from the viewing area, the classic schlieren method is obtained which provides a measure of density gradients themselves (Ref. 1).

2.2 LABORATORY SHADOWGRAPH

A laboratory-model shadowgraph system was set up to study the feasibility and applicability of using this technique for observing natural convection flows. A plexiglass water cell was used as the object for flow generation. The cell was lying "horizontal" on a bench with the heater plate on the bottom, i.e., a "heating from below" case. A schematic of this simple shadowgraph is shown on the following page.



The heater was connected to a power supply of 28 Vdc. A sequencing camera (Bolex H16 Reflex) was turned on at the onset of fluid motion and recorded the results of the test. The view is through the 1.27 cm side of the plexiglass container. The image recorded is inverted due to the lens, thus the film shows the following view:



Thermocouple probes are seen in the pictures as the view was focused on the "centerline" plane of the rectangular enclosure. The heater power was turned off when the plate temperature, monitored via thermocouple, reached $\sim 95^{\circ}C$. The film was recorded at 24 frames/second.

Sample data have been taken which indicate that the system can provide an adequate technique for optical visualization. Figures 1 and 2 are black and white still photographs taken using the laboratory apparatus. The viewing area is through the center portion of the water cell. The cell was lying horizontal, i.e., a heating-from-below orientation. The light and dark areas show qualitatively that convection was quite vigorous in this 1-g experiment. The 16 mm movie taken of the laboratory apparatus in operation, showed that the shadowgraph is satisfactory for resolving vigorous natural convection.

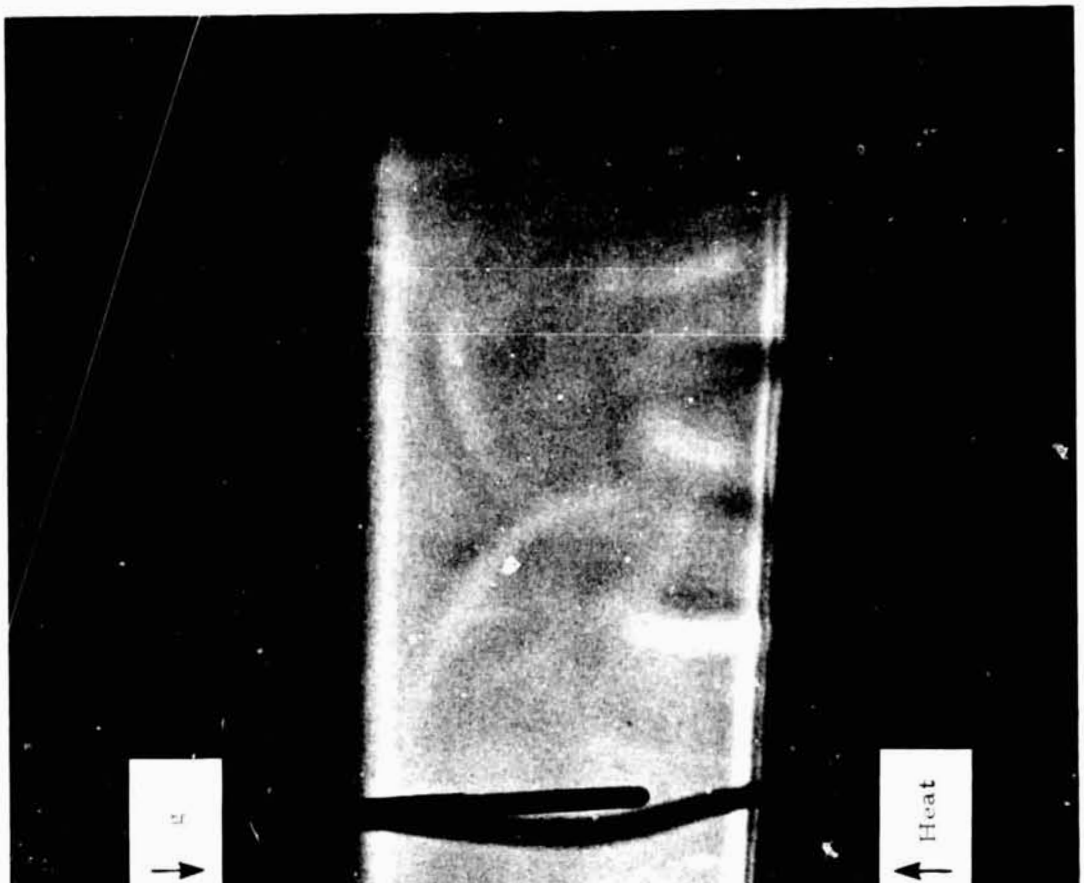


Fig. 1 - Photograph of Laboratory Shadowgraph at t=2 Minutes after Heating

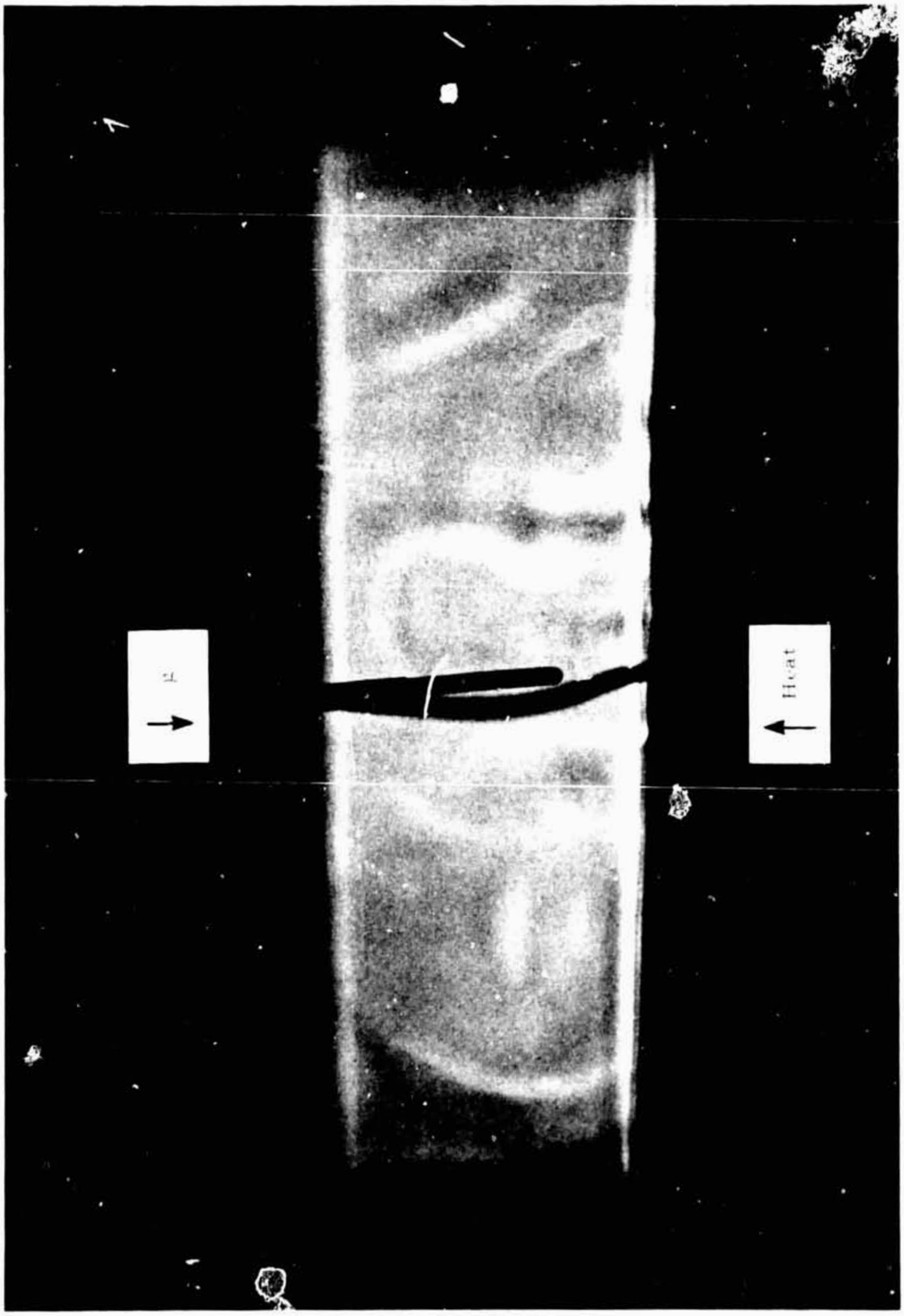


Fig. 2 - Photograph of Laboratory Shadowgraph at t= 10 Minutes After Heating

2.3 SYSTEM DESIGN

In order for the optical system to "fit" an existing hardware package and to remain compatible with size contraints aboard spacecraft, the optics were "folded" using a series of mirrors. A schematic of the shadowgraph with folded optics is given in Fig. 3. The light source is reflected through the mirrors, the collimating lens and into the modular test cell. The output is again reflected by mirrors into the camera. Baffles and light shields were used to block out extraneous sources and an enclosure was used to maintain the optical system intact.

The light source is a Zirconium Arc Lamp (Edmund Scientific, C25) rated at 25 volts, 25 watts. The mirrors are aluminized with a silicon oxide overcoat (Oriel Optics Corporation A-45). The lens are Ealing Optical Corporation 23-8428 type having a diameter of 95 mm and focal length of 130 mm. The camera used was the standard NASA Data Acquisition Camera ( ) used on the Apollo flights (SEB 33100100, 28 volts dc). Power can be ed to the DAC and the light source through appropriate control modules, which obtain the needed 28 volts.

The laboratory shadowgraph with "folded optics" was set up for evaluation of the technique. A wood frame was fabricated to mount the components. This approach was used to keep the cost at a minimum since this apparatus is for ground testing only. The zirconium arc lamp is connected to a 28 Vdc power supply. A plexiglass rectangular container of water was the test object. The entire structure is mounted inside a plywood enclosure, painted flat black to eliminate extraneous light sources. Movies were made using ASA 320 reversal black and white film. The f-stop was varied from f = 2 to 4 to 8. Density gradients were induced in a plexiglass box of water by injecting alcohol at the surface. The movies were made at 24 frames/second. The movies were made successfully and showed adequate resolution of the density gradient contours. The best resolution was obtained with f = 8. For the other f-stop values, the film was too bright and not enough contrast was obtained. Also the quality of

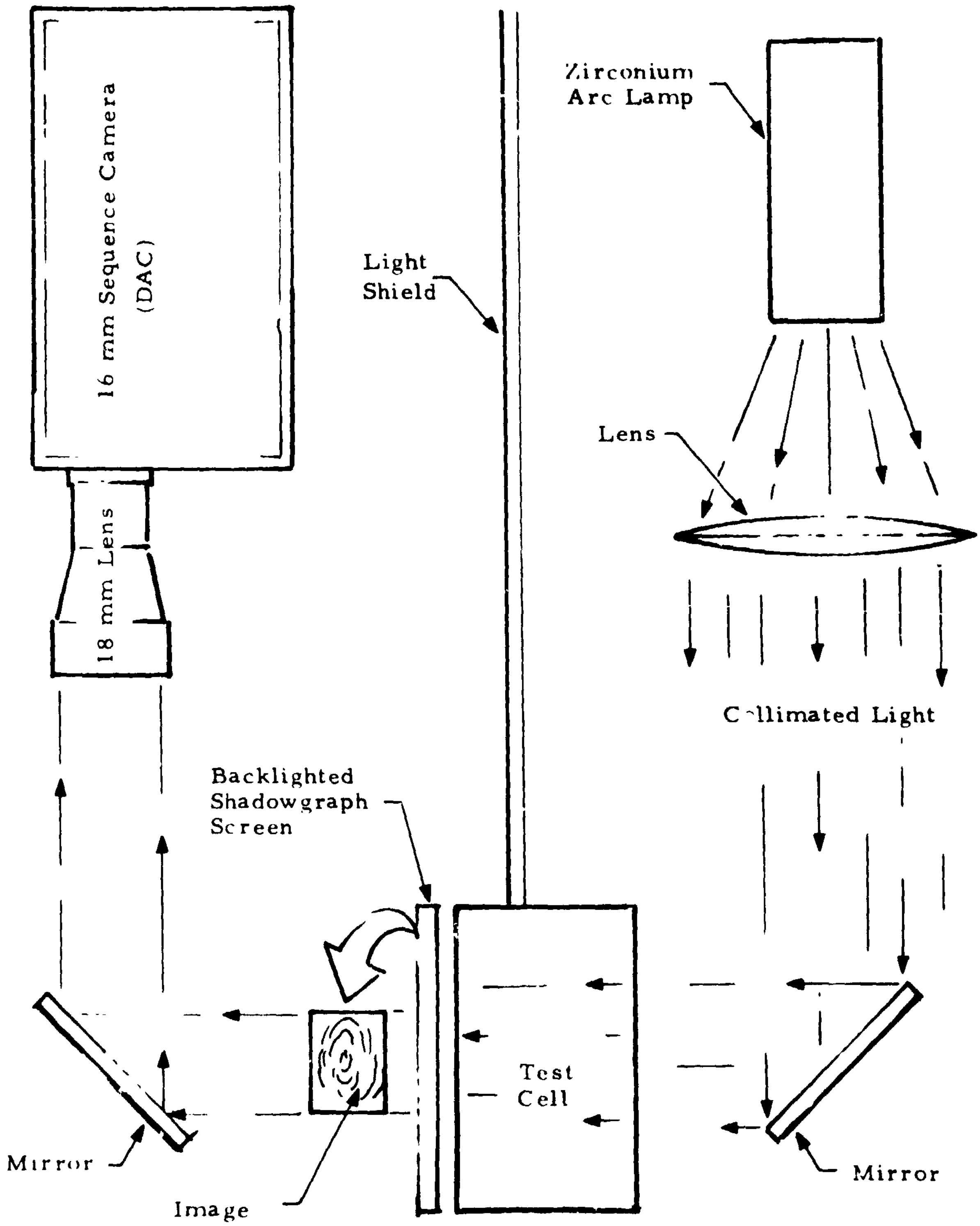


Fig. 3 - Schematic of Flow Visualization System Preliminary Design

the ASA 320 film which was used does not appear to be totally satisfactory. However, the movies do seem to verify that the "folded optics" shadowgraph is adequate for studying natural convection flows.

This design appears to be optimum in terms of resolution of data, size and weight constraints, and compatibility with existing flight hardware (Ref. 5)

2.4 INTEGRATION

An optical visualization on flight apparatus can be developed by modifying existing hardware (Ref. 5). Figure 4 is a photograph showing a convection measurement package designed for space flight. This hardware is suitable for the Black Brant sounding rocket. The package measures 35 cm in diameter and approximately 33 cm in height. The weight of the package shown is 16.1 kilograms. The two enclosed modules contain the power controllers, amplifiers, thermocouple reference junctions and associated electronics. The package as shown in Fig. 4 contains two test cells. A plan for constructing a flight visualization apparatus consists of modifying this package by removing the cylindrical cell and adding the optical visualization hardware. The water cell module would remain as shown. Figure 5 is a schematic showing a possible integration scheme. This arrangement provides a working system while maintaining the existing dimensions and hardware orientation.

2.5 DATA ANALYSIS PROCEDURES

The shadowgraph technique gives only qualitiative data since the image formed is a result of the light traveling through the "length" of the flow field. However, by coupling an optical analysis to the Lockheed Convective Flow program (Ref. 6) it may be possible to obtain quantitative data from the shadowgraph. The approach for analyzing these data is as follows.

Consider the geometry dipicted in Fig. 6 where a collimated light source is being passed through a flow field and imaged onto a screen as shown to produce a shadowgraph. Let us assume that the source can be well

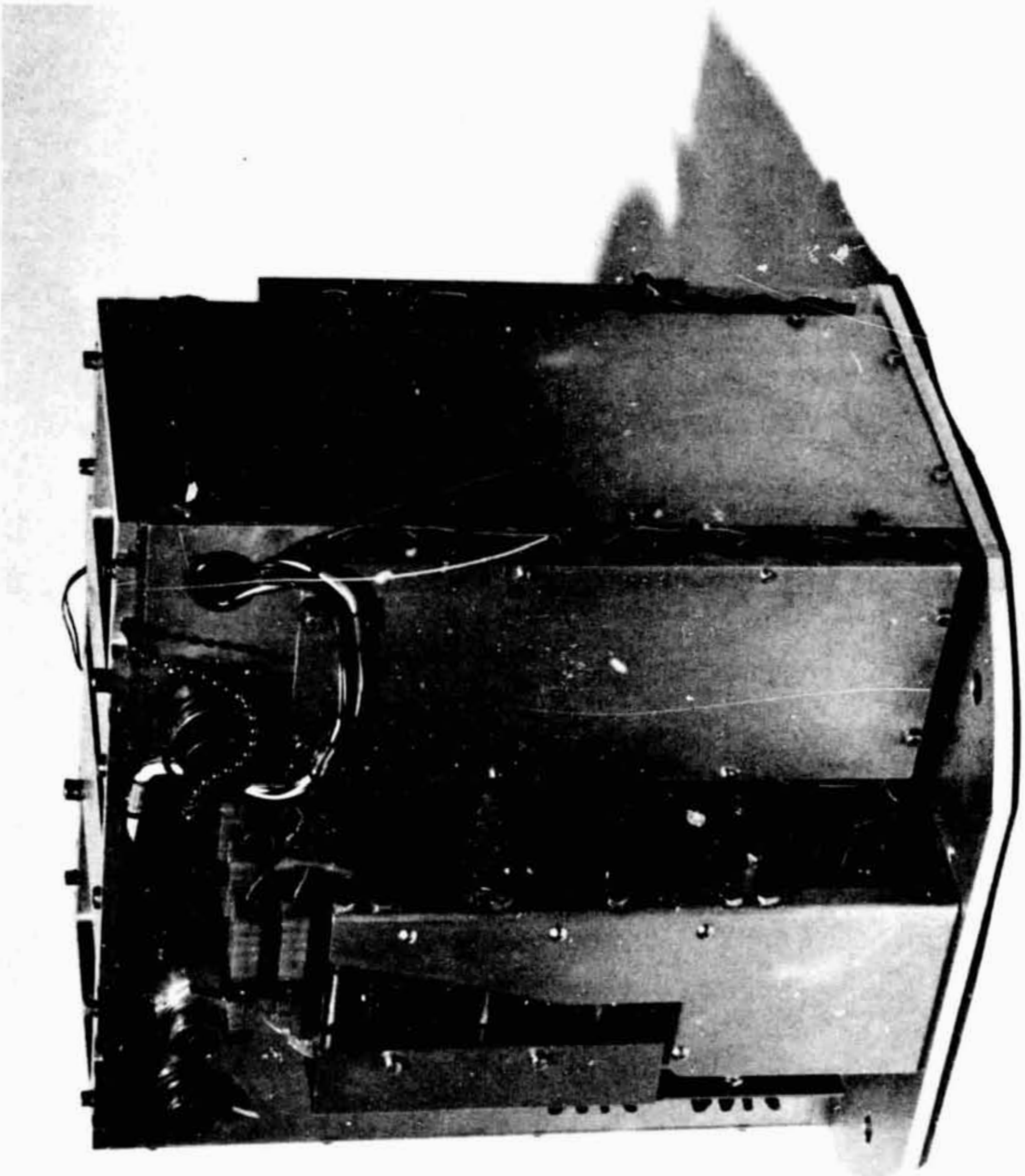


Fig. 4 - Photograph of Basic Apparatus to be Modified for Optical Visualization System

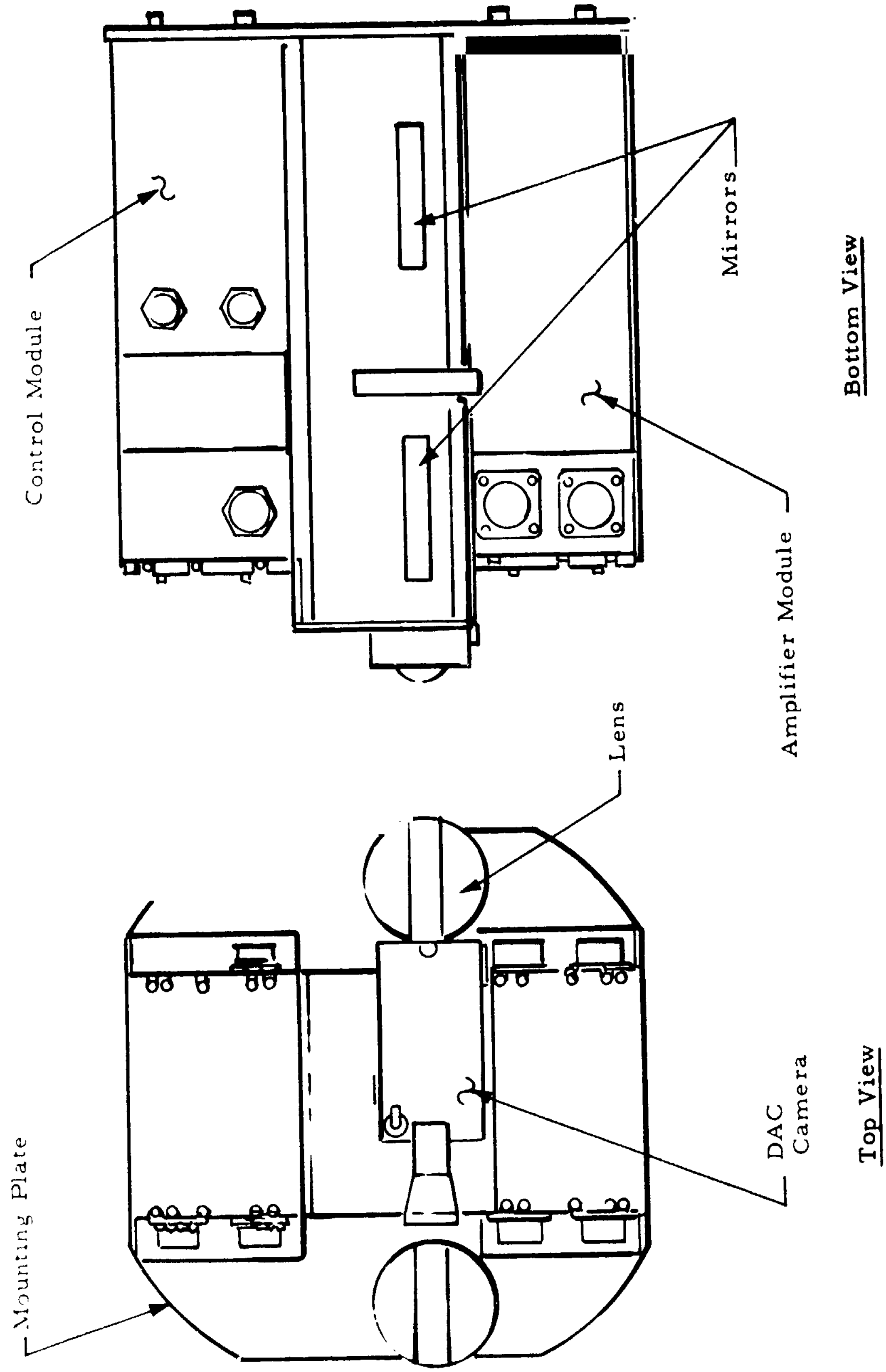


Fig. 5 - Arrangement of Optical System for Compability with Existing Hardware (Fig. 4)

characterized in terms of its intensity and degree of collimation. Consider the three typical rays R_o, R_1, and R_2. At x = 0 assume the distance between R_o and R_1 is equal to that between R_1 and R_2, i.e.,

$$\epsilon_1 = \Delta y = \epsilon_2$$

Due to the variation in the index of refraction of the fluid in the flow field, these rays can converge or diverge as they propagate through the fluid. Let us assume that the flow field is such in the region bounded by R_o and R_1 that the rays diverge, i.e., ϵ_1' on the shadowgraph screen is greater than ϵ_1. Also let us assume that in the region bounded by R_1 and R_2 the rays converge, i.e., $\epsilon_2' < \epsilon_2$. If the two regions are receiving the same amount of light from the source then the area ϵ_1' will appear as a darkened area and ϵ_2' will appear as a bright area, i.e., the illumination of the shadowgraph screen is dependent on the spatial change of the deflection of the rays.

$$\Delta E \propto \vec{\nabla}\epsilon$$

The deflection, however, is a function of the spatial change of the index of refraction of the fluid along the ray path.

$$\epsilon \propto \vec{\nabla} n\,(x, y)$$

Thus

$$\Delta E \propto \nabla^2 n\,(x, y)$$

The index of refraction can be expressed as a function of the density. If the index of refraction is directly proportional to the density (this is a good first order approximation for many fluids) then

$$\Delta E \propto \nabla^2 \rho(x, y)$$

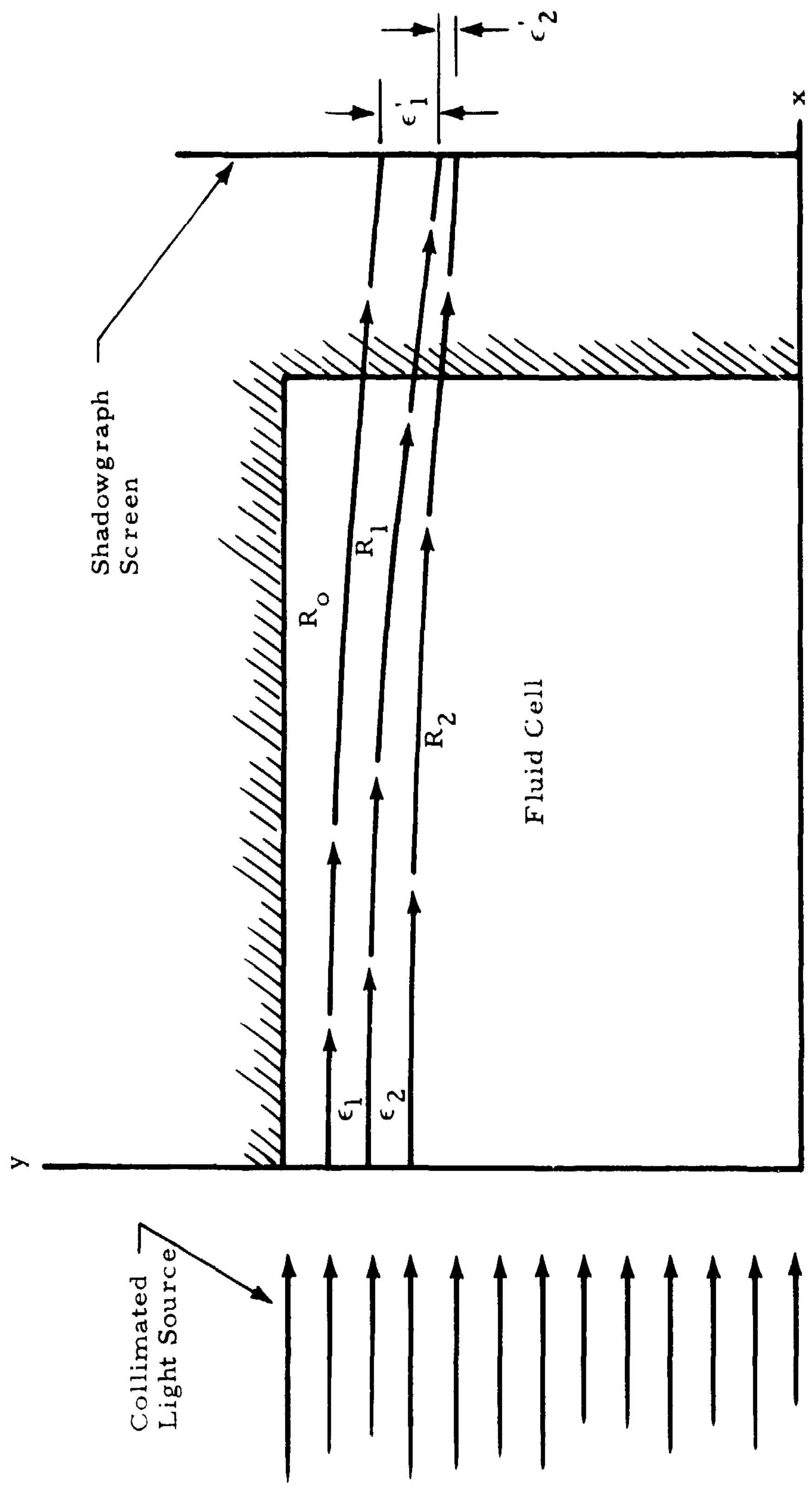


Fig. 6 - Shadowgraph Data Analysis Procedure

From the above it can be seen that the shadowgraph results depend on the density throughout the flow field. Let us assume that an accurate method is available for predicting $\rho(x, y)$ such as the Lockheed Convective Flow program. With this information, which would yield $n(x, y)$, and application of geometric optics one could trace rays through the flow field and thus analytically generate a shadowgraph. The ray tracing can be handled by application of Fermat's principle. For the present situation this results in the following differential equations.

$$\frac{d}{ds}\left(n \frac{dx}{ds}\right) - \frac{\partial n}{\partial x} = 0$$

$$\frac{d}{ds}\left(n \frac{dy}{ds}\right) - \frac{\partial n}{\partial y} = 0$$

where $ds = \sqrt{(dx)^2 + (dy)^2}$. These differential equations can be integrated numerically.

Thus by application of the above ideas it may be possible to reproduce experimental shadowgraph results analytically. This would verify the flow-field analysis and the quantitative information which the analysis predicts.

Section 3
CONCLUSIONS AND RECOMMENDATIONS

This study has investigated an optical visualization system for natural convection in low gravity. A literature survey was performed to evaluate possible candidate systems. A laboratory shadowgraph was set up to study the resolution of density gradient contours in a heated container of water. The results of the study indicate that a shadowgraph technique is adequate for detecting convection flow patterns. A design using folded optics was developed for application to a space flight unit. A possible integration scheme for use with an existing hardware package was devised. Finally, a data reduction and analysis plan for quantifying the shadowgraph was presented.

As a result of this study, it is recommended that a flight apparatus be developed using the shadowgraph technique. A flight test program should then be conducted to study the convective flow patterns in low gravity. The NASA Sounding Rocket Program provides an excellent opportunity for this type of investigation. An investigation can be designed to accomplish several objectives by performing a series of experiments aboard sounding rockets. The goals for such a study should be:

- To provide a means of determining the effects of diffusion and/or convection on space manufacturing processes such as crystal growth and electrophoresis or other separation procedures
- To provide an apparatus capable of repeated use by multiple investigators on subsequent flights
- To obtain a measure of the convection levels aboard the rockets for assessment of the environment of rockets for various space manufacturing experiments

A logical extension to the initial study could be:

- To design, develop and flight test a crystal growth and material separation experiment module utilizing the optical visualization apparatus
- To make a definite assessment of the effects of low-g convection on crystal growth and material separation processes
- To extrapolate the findings of this study in order to provide other experiment Principal Investigators with conclusive quantitative information on lack or presence of convective effects aboard the rockets.

Section 4
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