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IIT Research Institute

IITRI Final Report No. D6137

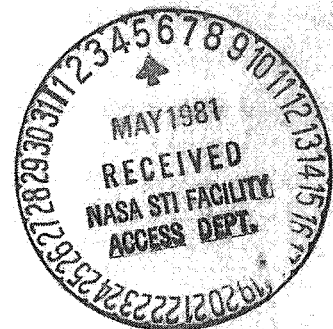
SPACE PROCESSING OF CHALCOGENIDE GLASS

for

National Aeronautics & Space Administration
George C. Marshall Space Flight Center
Alabama 35812

Contract No. NAS8-32388

7 March 1977 - 30 September 1978



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Prepared by:

R. F. Firestone and S.W. Schramm

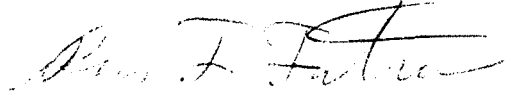
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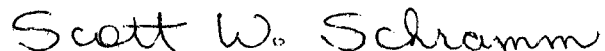
FOREWORD

The work described in this report, Final Report No. D6137 entitled "Space Processing of Chalcogenide Glass," was performed under the sponsorship of the Marshall Space Flight Center. The work was conducted under Contract No. NAS8-32388, over the period March 7, 1977 to September 30, 1978, at IIT Research Institute. The Principal Investigator was Dr. R. Firestone and Mr. S. Schramm was the Project Engineer. We are pleased to acknowledge the valuable assistance and counsel of Mr. R.L. Nichols, NASA/MSFC Contracting Officer's Representative on this program.

Respectfully submitted,
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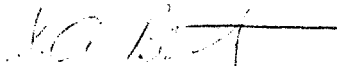


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ABSTRACT

A program has been conducted to develop the technique of space processing for chalcogenide glass, and to define the process and equipment necessary to do so. In the course of this program, successful long term levitation of objects in a 1-g environment has been achieved. Glass beads 4mm diameter have been containerless melted and fused together.

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SPACE PROCESSING OF CHALCOGENIDE GLASS

1.0 INTRODUCTION

This program on space processing of chalcogenide glasses is a follow-on to previous work conducted under Contract No. NAS8-30627. The overall goal was to produce better infrared transmitting chalcogenide glasses through containerless processing provided by the microgravity environment of space. Previous work mainly involved production of high quality $\text{Ge}_{28}\text{Sb}_{12}\text{Se}_{60}$ glass by conventional methods. The primary goal of the current program was to develop specific techniques to utilize acoustic levitation at high temperature to achieve a containerless condition in a ground-base program prior to an actual space mission.

Chalcogenide glasses are good infrared transmitters and have good strength, corrosion resistance, and scale-up potential. For these reasons, chalcogenide glasses are considered potential candidate materials for use as laser windows and as infrared fiber optics for transmitting a laser beam through a flexible probe. For fiber optics, it has previously been demonstrated that high quality chalcogenide fiber optics could not be processed due to limitations related to the presence of the 1-g earth environment.

The overall objective of IITRI's current program is to determine the manner in which the weightless, containerless nature of in-space processing can be successfully utilized to improve the quality of infrared transmitting chalcogenide glasses. This program was an effort to develop the technique of space processing chalcogenide glass, and define the process and equipment necessary to do so. These goals are accomplished by a series of earthbound (1 g) experiments with an acoustic levitation device that will eventually be used to achieve position-controlled containerless processing in a space environment (10^{-4} g).

To achieve this goal, IITRI was supplied an improved acoustic position control/levitation device manufactured for MSFC by Interasonics, Inc., Chicago, Illinois. This device is termed improved in the sense that it was specifically designed for long term, high temperature, levitation under 1-g conditions. The necessity of such improvements resulted from IITRI's experience with another Interasonics MSFC levitator on our previous program.

2.0 CONCEPTS OF SPACE PROCESSING

The principle being used in this program is to take advantage of the near zero "g" environment of space to reduce foreign material contact with melt by containerless melting, and to eliminate the thermal currents in the melt. It is the defects caused by earth environmental manufacture that causes the glass to overheat in local areas and to fracture when exposed to large amounts of infrared radiation. Also, smaller amounts of radiation, although not sufficient to cause thermal fracture, will have distorted wave forms and thus degrade the value of the signal. Therefore, these imperfections must be eliminated.

To accomplish the intended improvement in chalcogenide quality, the high-temperature process for making the glass must be carried on in space at zero "g" where weightless, containerless conditions can be obtained. The preparation for compounding and the final treatment of the material for an optical element can be done on earth without reducing the quality of the space-processed material.

3.0 EARTH PROCESSING VS. SPACE PROCESSING OF CHALCOGENIDE GLASSES

The earth-bound production of chalcogenide glasses involves a five step process: 1) the elemental precursor powders are placed in a silica ampoule; 2) the ampoule is evacuated and sealed; 3) the temperature is slowly increased to the reaction temperature to form the compounded liquid; 4) the ampoule is rocked back and forth for periods up to 48 hours to homogenize the liquid; and 5) the liquid is quenched to form a glass.

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The rocking of the ampoule and the resulting mixing of the liquid is necessary to overcome the micro-inhomogeneities resulting from thermal currents and density fluctuations that are due to the presence of the earth's 1-g gravity field. However, these gravity related phenomena are never completely eliminated by this method. Furthermore, this prolonged contact with the crucible material contaminates the chalcogenide with ppm levels of oxygen and other elements deleterious to ir-transmission at a wavelength of 10.6μ .

By going to space to process chalcogenide glasses, both of these problems, thermal currents/density fluctuations and contamination, will be eliminated. The compounding and quenching aspects of the process can be performed in the absence of gravity, eliminating thermal convection. The zero gravity condition provides for the possibility of containerless processing which will eliminate the contamination effects of the earth melting crucible. Thus, the weightless, containerless aspects of space manufacture has the potential for producing an improved ir-transmitting chalcogenide for use as a large diameter 10.6μ window.

4.0 RESEARCH PROGRAM

The objective of the program was to conduct the research necessary to prepare chalcogenide glass material samples and to design the experiment for flight aboard the Space Shuttle or other longer duration space flights.

The program was divided into the following tasks:

Task 1. Determine the techniques and establish the working parameters for long term (approximately 9 hours) levitation of $\text{Ge}_{28}\text{Sb}_{12}\text{Se}_{60}$ in a 1-g environment using the acoustic levitator provided by NASA/MSFC.

Task 2: Determine the feasibility of complete processing of $\text{Ge}_{28}\text{Sb}_{12}\text{Se}_{60}$ without a container using the acoustic levitator.

Task 3: Determine the feasibility of drawing fibers from molten $\text{Ge}_{28}\text{Sb}_{12}\text{Se}_{60}$ glass using the acoustic levitator.

Task 4: Investigate the feasibility of shaping $\text{Ge}_{28}\text{Sb}_{12}\text{Se}_{60}$ glass lenses and windows using the acoustic levitator.

Task 5: Design a space experiment for processing bulk $\text{Ge}_{28}\text{Sb}_{12}\text{Se}_{60}$ glass and describe the techniques for each step of the process.

In order to carry out this program it was crucial to make the acoustic levitator work reliably. The experience with the levitator on the previous program was not encouraging and, indeed, almost all of the time and resources of the current program were required before reliable levitation was achieved.

4.1 Acoustic Levitation

Acoustic levitation uses sound waves to support objects in space. Sound waves are pressure variations in the air, alternate densifications and rarefactions, which travel at a nearly constant velocity from their source. If the waves are reflected, and a static sound field is set up, objects may be supported at planes of minimum pressure (nodes) as shown in Figure 1. These planes are not flat but are undulating so that the object is constrained within a pressure well as shown in Figure 2. The existence of these wells can be demonstrated experimentally by placing objects in the sound field as shown in Figure 3 in which a styrofoam bead is supported in each of five nodes.

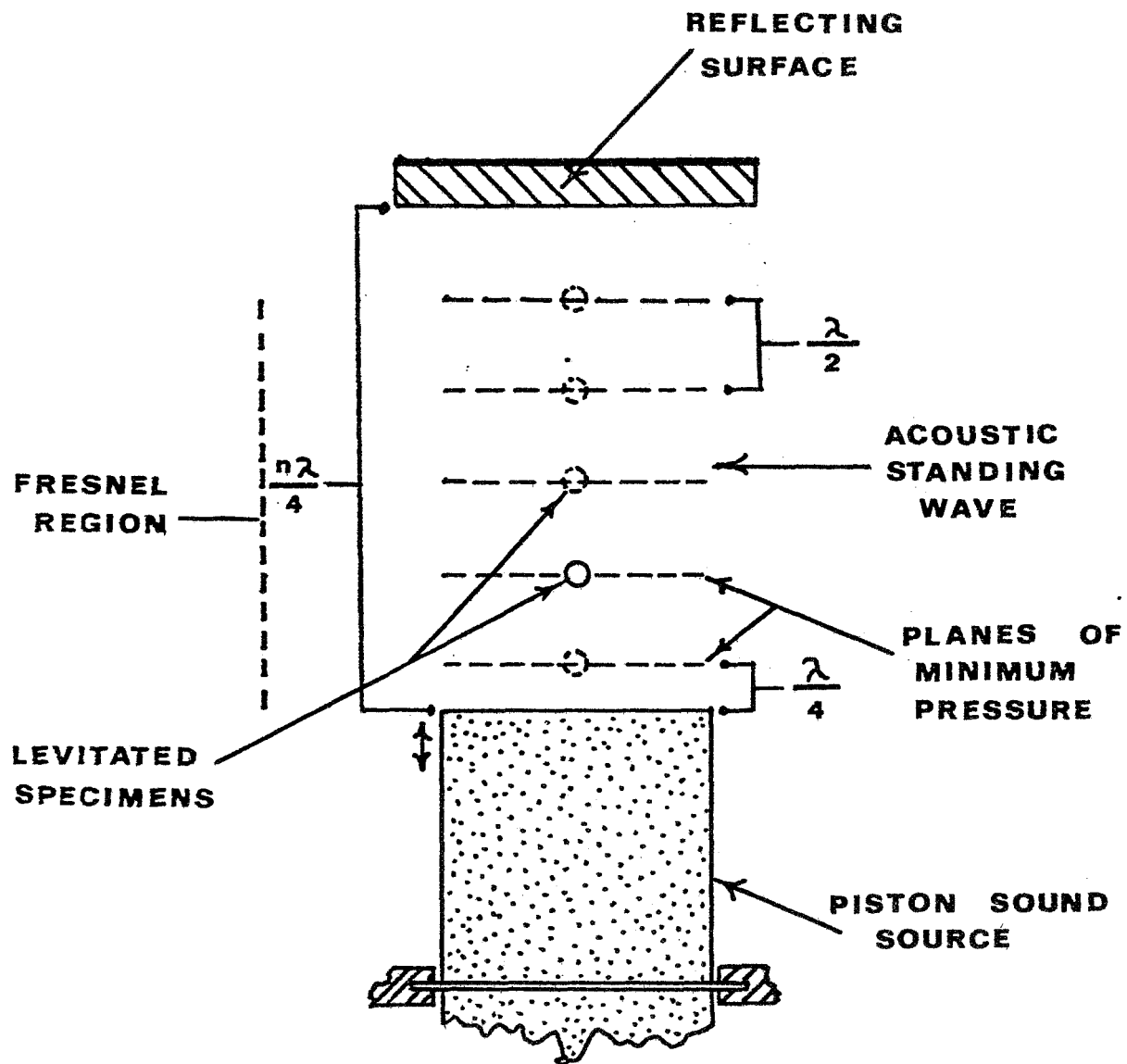


FIGURE 1. THE ENERGY WELL LEVITATOR
(Whymark 1974)

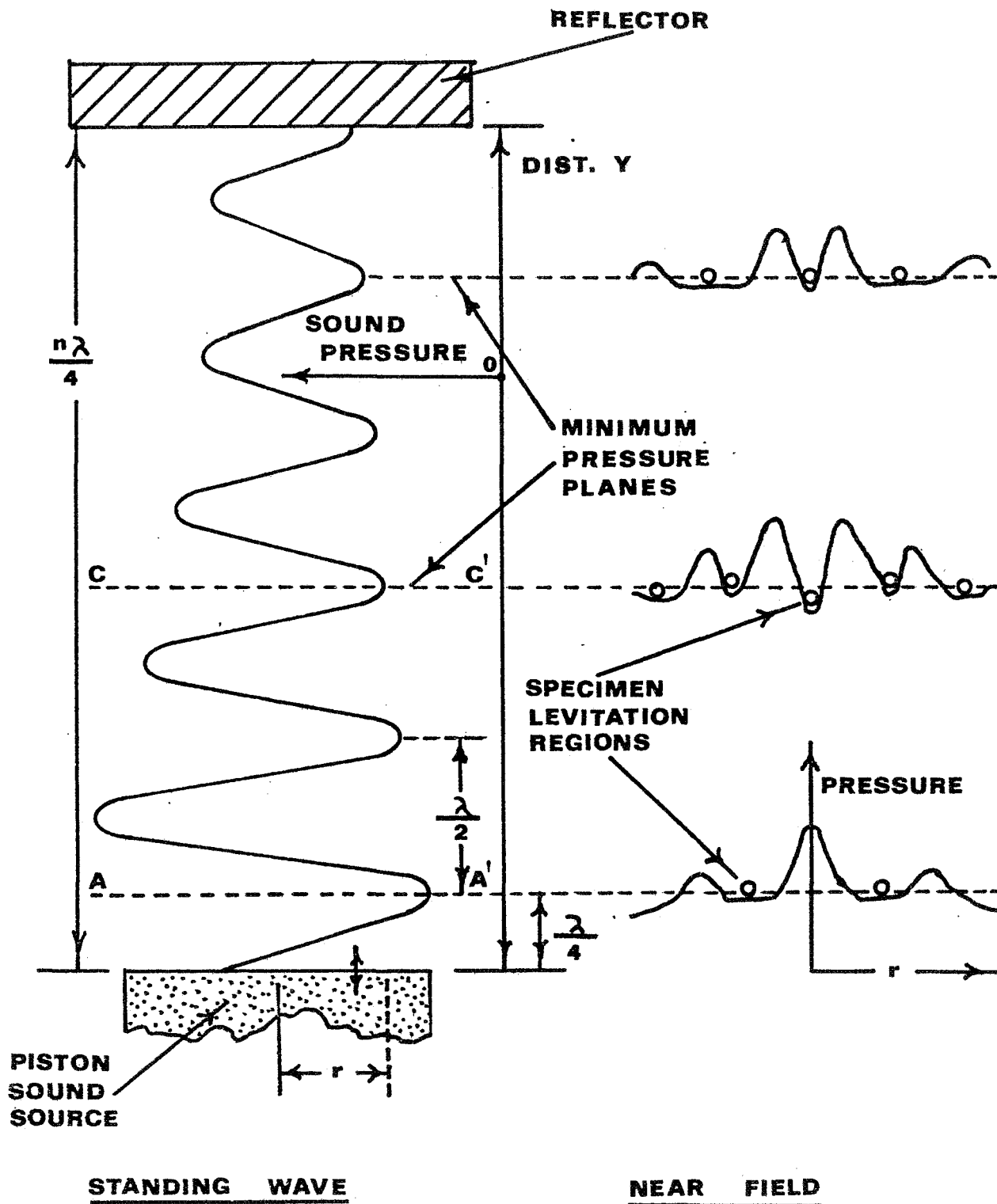


FIGURE 2. DISTRIBUTION OF SOUND PRESSURE
(Whymark 1974)

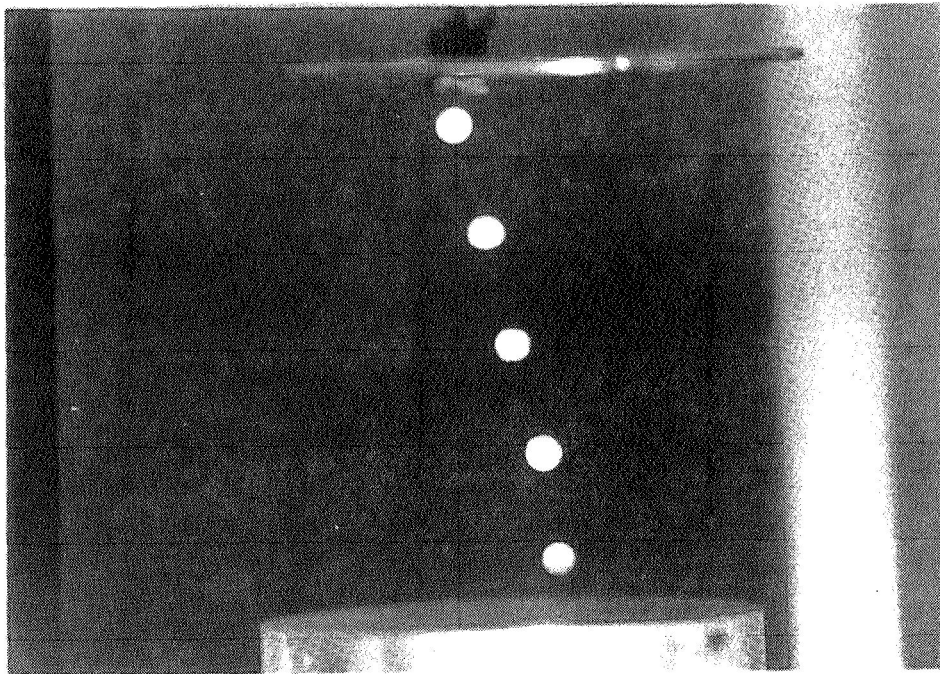


Figure 3. Styrofoam Beads Supported at Planes of Minimum Pressure in Acoustic Levitator (1.X)

An object is stably levitated when the downward force, F_g , due to gravity is just balanced by the upward force, F_a , due to the acoustic field. The forces are given by the following relations:

$$F_g = mg \quad (1)$$

where "m" is the mass of the object and "g" is the acceleration of gravity, and:

$$F_a = pA \quad (2)$$

where "p" is the acoustic field pressure and "A" is the area of the object perpendicular to the field.

At equilibrium

$$F_g = F_a \quad (3)$$

Substituting relations (1) and (2) in (3) and rearranging;

$$p = g(m/A)$$

where "m/A" is the sectional density. Of the four parameters, the mass, m and the acceleration of gravity, g, are fixed but the acoustic field pressure, p, is experimentally adjustable by varying the input power to the levitator, and the cross-sectional area, A, can be varied by changing the shape of the object. Thus, for the same mass, a disc is more easily levitated than a sphere, since its sectional density is less.

4.2 Acoustic Levitator Device

The acoustic levitator was the crucial device for the research program since all tasks require its use for their successful accomplishment. The device used was the Model 15-1A Acoustic Levitator which was supplied by Intersonics, Inc., Northbrook, Illinois, and has been described by Whymark (1974)¹. It was developed for NASA/MSFC and supplied GFE to IITRI for use on the program.

¹ R.R.Whymark, "Acoustic Field Positioning For Containerless Processing," Procedures Third Space Processing Symposium Skylab Results. NASA-MSFC, May 1974.

This acoustic levitator had been used on the previous chalcogenide glass program with little success since stable levitation could not be achieved, even at room temperature. At the end of the previous program, it had been returned to Intersonics for repair. After it was repaired, IITRI personnel spent a day at Intersonics to gain operational experience with the instrument before it was returned to IITRI at the beginning of the first quarter of this program.

Initial experiments disclosed that the levitator was still not capable of stable levitation for longer than 15 minutes; either the objects were ejected from the device or the device failed. Strong and persistent interaction between IITRI and Intersonics resulted in the repair of the unit by Intersonics personnel. The device worked well during the rest of the program and it is, we hope, finally "debugged".

The acoustic levitator consists of two parts: a driver unit, and a power unit containing an oscillator, amplifier and power supply. The unit is self-tuning with a nominal operating frequency of 15 kHz. power input of approximately 300 watts; the sound output from the driver is greater than 160 db at a distance of 6 inches. A round steel reflector with an axial center hole was provided, but any dense material would appear to be suitable for use as a reflector.

Operation of the levitator appears deceptively simple since there are only three controls: gain, which varies the input power, high-low, and the distance between driver and reflector. The high-low switch is not critical; however, the other two require exquisite adjustment if stable levitation is to be achieved. For high temperature operation, the controls require delicate and constant manipulation to maintain levitation during temperature changes. Although an operating manual was provided by Intersonics, Inc., it is not sufficiently detailed for successful operation. The operating procedure developed at IITRI is given in the Appendix.

For high temperature experiments, a small silicon carbide heating element furnace insulated with firebrick was supplied by Intersonics, Inc. The temperature was controlled by varying the power input. It proved to be impossible to obtain stable levitation in the furnace as received. After prolonged experiment, the furnace was completely rebuilt using fibrous insulation to obtain an anechoic furnace in which the only reflection of sound was from the reflector surface parallel to the driver at the top of the furnace.

4.3 Experimental Results

The set up for room temperature acoustic levitation is shown in Figure 4. The small bead in the center of the picture is being levitated between the reflector above and the drive piston below. The drive unit is cooled by both water and air. The microphone in the center foreground is used in conjunction with an oscilloscope to monitor the sound output. The details of the setup are discussed in the Appendix.

After the final repair of the device, various acoustic levitation experiments were conducted at room temperature. Initial experiments were conducted with styrofoam spheres and disc. These were used to find the pressure planes in the acoustic standing wave between the driver and reflector. Five planes were located as can be seen in Figure 3 in which a single sphere is located at each plane. The most intense plane is the center one. Multiple spheres were used to define its extent as shown in Figure 5. The "plane" as shown by the position of the spheres is approximately a concave down spherical zone of one base with a diameter of 1 inch and a depth of 1/8 inch.

The experiments were repeated with 4mm diameter soda-lime glass beads; first with one bead on the center plane (Figure 6), then three (Figure 7), then six (Figure 8), and finally fifteen (Figure 9). The layer of multiple beads assumed a close packed configuration and layers with trigonal symmetry were the most

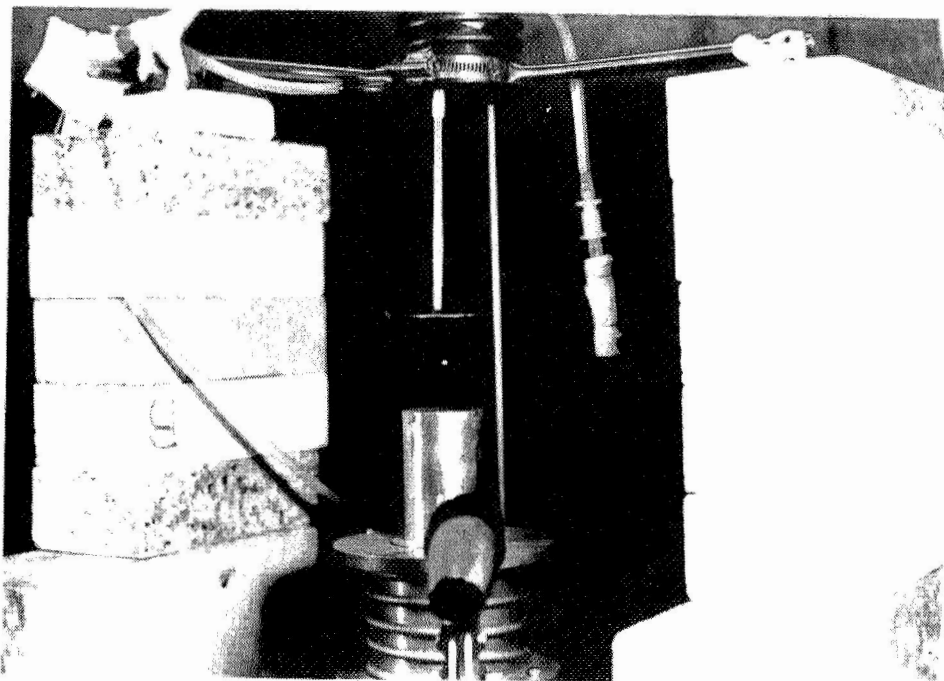


Figure 4. Room Temperature Acoustic Levitation Setup

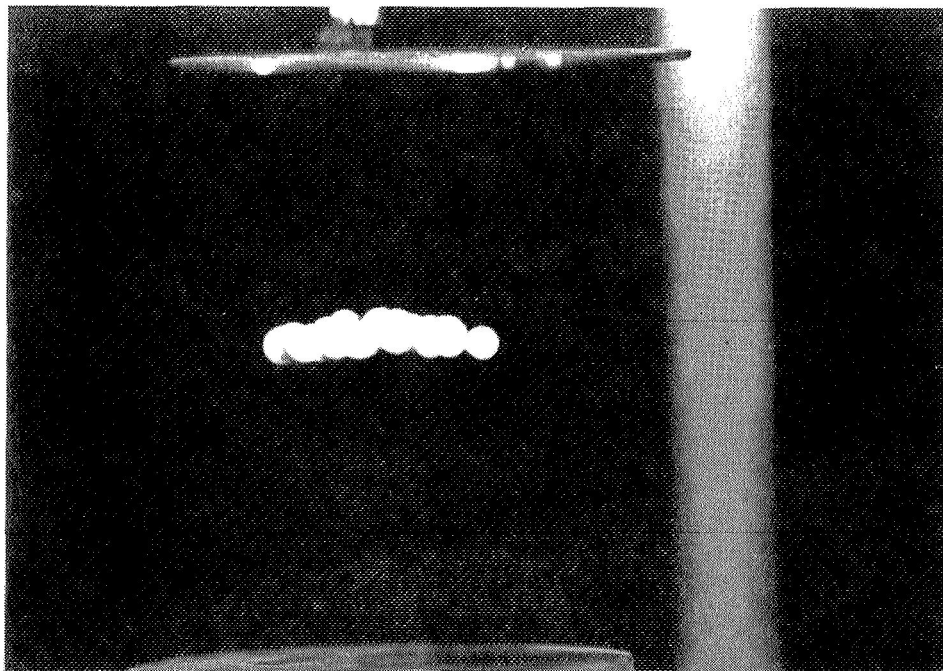


Figure 5. Multiple Styrofoam Spheres on Single Minimum Pressure Plane (1.3X)

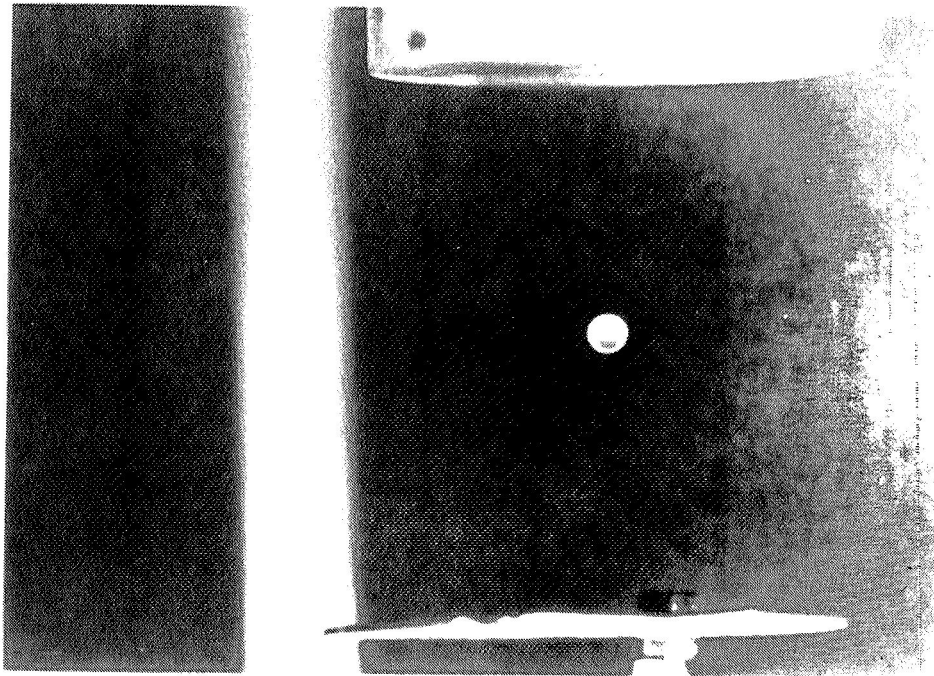


Figure 6. Levitation of Single 4mm Glass Bead (1.3X)

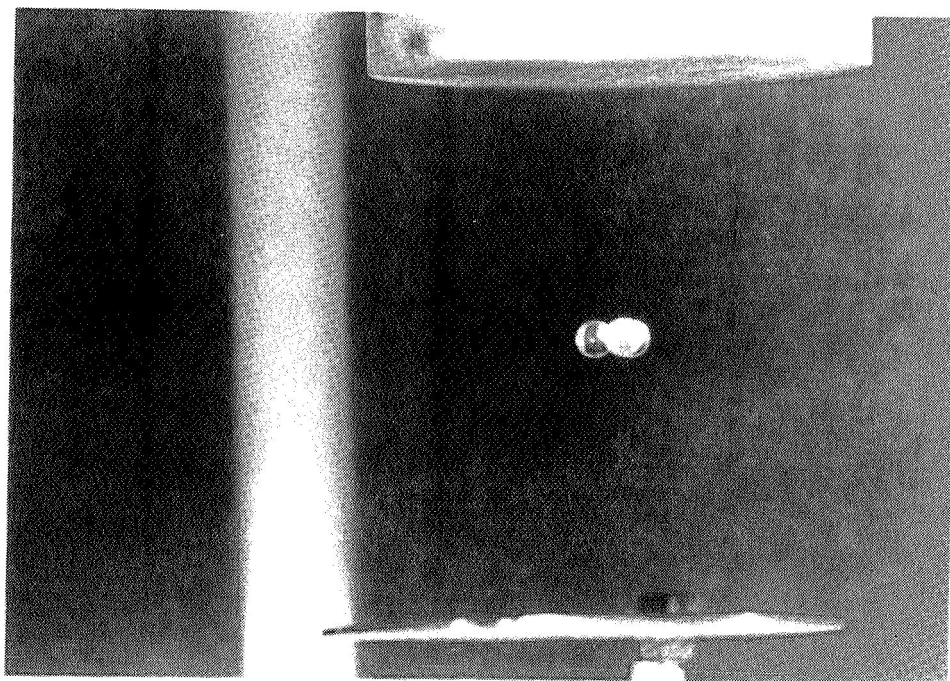


Figure 7. Levitation of Three 4mm Glass Beads (1.3X)

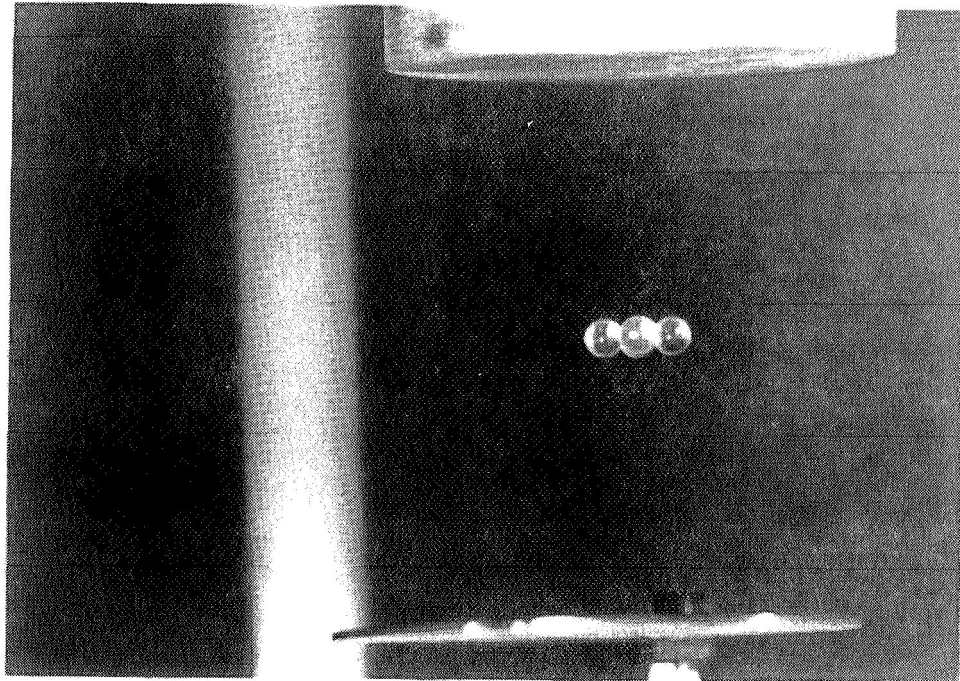


Figure 8. Levitation of Six 4mm Glass Beads (1.3X)

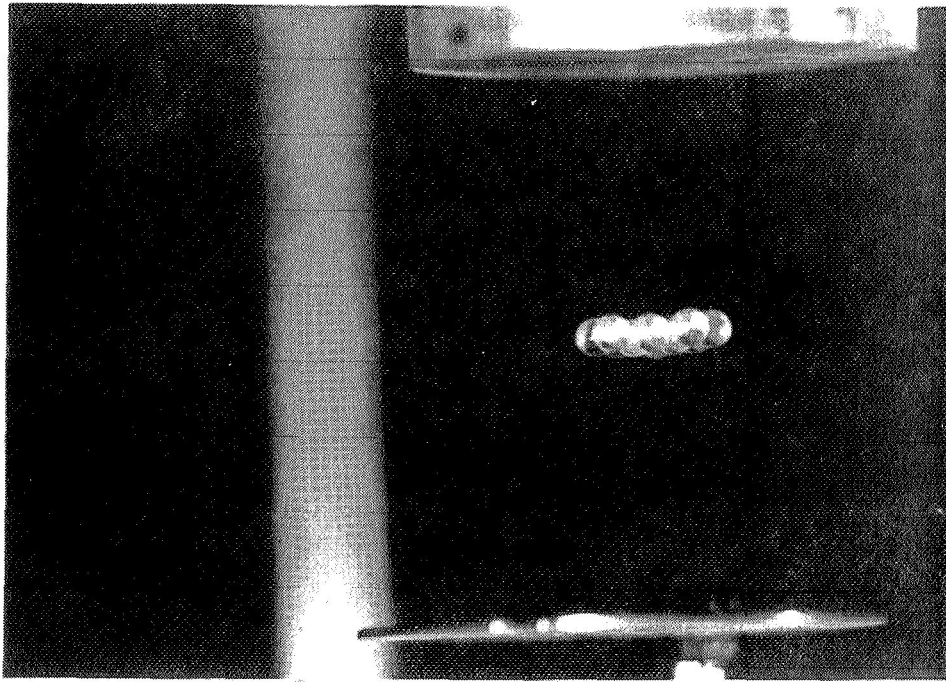


Figure 9. Levitation of Fifteen 4mm Glass Beads (1.3X)

stable. By adjusting the levitator, the bead(s) could be rotated, either slowly or so rapidly that the centrifugal force ejected the outer beads of a multiple bead layer from the levitator field. It was also found that a glass bead could be levitated at each of the five nodes (Figure 10).

Stable levitation of single or multiple glass beads was achieved for long periods of time at room temperature. A single 4mm glass bead was levitated for seven hours, the longest time any object was levitated in this program. It showed no instability from the start of the levitation until it was electively removed at the end of the day. It is our opinion that the levitation could have been continued indefinitely.

A variety of other objects were levitated: 4mm drop of water, 8mm polymethylmethacrylate spheres, 18mm diameter by 1mm thick copper-silver disc (1965 Roosevelt dime, Philadelphia mint), and 20mm diameter by 3mm thick aluminum discs. The properties of these objects are listed in Table I.

The water drop levitation showed that the acoustic field not only supported but also confined small objects, even though the pressure "plane" is concave down. Since the viscosity of water is similar to molten chalcogenide glass, this suggests that the glass can also be levitated and contained when molten, if its surface energy is high enough.

Experiments to melt levitated objects were not as successful. Even the modified furnace perturbed the sound field and increased the instability, while the lower density of high temperature air provided less support. In initial experiments, a stinger was used to center the object in the field and gobs of lithium borate glass were melted at 500°C. However, the glass wet the stinger (a 3 mil diameter fused silica fiber) so that the acoustic field had only a small effect.

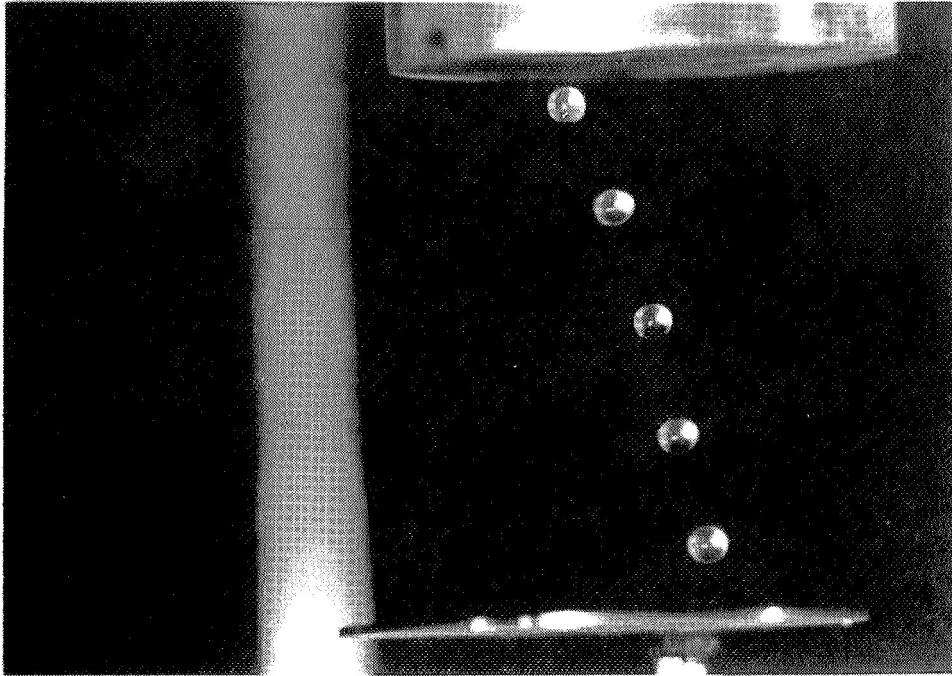


Figure 10. Levitation of Five 4mm Glass Beads (1.3X)

Table I - Properties of Objects for Levitation

Object	Weight, grams	Dimensions	Volume, cm ³	Density, g/cm ³	Sectional Area cm ²	Sectional Density, g/cm ²
4mm Styrofoam Bead		.4cm dia.	.033	0.1	.126	0.028
4mm Soda-Lime Glass Bead	.086	.41cm dia.	.036	2.4	.13	0.66
4mm Chalcogenide Glass Bead	.215	.4cm dia,	.033	~6	.126	1.77
Cooper-Silver Disc (US dime)	2.24	1.8cm dia .1cm thick	.254	8.8	2.54	0.88
Aluminum Disc.	2.54	.2cm dia. .3cm thick	.942	2.7	3.14	0.81

Pneumatic stabilization and levitation was investigated as a supplement to acoustic levitation for high temperature experiments. It showed promise for increasing the stability of irregular objects during melting. However, refinement of the acoustic levitation technique made pneumatic stabilization unnecessary.

Melting of single and multiple 3mm and 4mm soda-lime glass beads at 615°C without a stinger has been accomplished. A picture of a melted and cooled 4mm bead is shown in Figure 11 with an unmelted bead for comparison. The molten bead has become oblate like a water drop.

Multiple beads were also levitated and melted. In one case, a layer of four 4mm diameter beads were levitated and melted. Two of the beads fused together and are shown in Figure 12. The location of the connection at the common diametrical center line of the beads shows that the joining occurred while levitated. The ripples on the beads' surfaces are due to glass flow.

Unfortunately, in all the melting experiments, the glass beads were ejected from the levitator as soon as they were melted due to the sudden decrease in sectional density. When a glass bead is containerless melted, two changes occur: the density decreases and the shape becomes oblate. The changes cause the sectional density to decrease so that the acoustical force, F_a , is no longer in equilibrium with the constant gravitational force, F_g , see Figure 13. The upward resultant of the forces bounces the bead against the reflector and out of the levitator.

If the acoustic force could be lowered rapidly enough to maintain equilibrium during the transition from solid to liquid, the object could be retained in the levitator. Numerous attempts at controlling the force manually were unsuccessful. It was concluded that a feed back circuit using a position sensor to

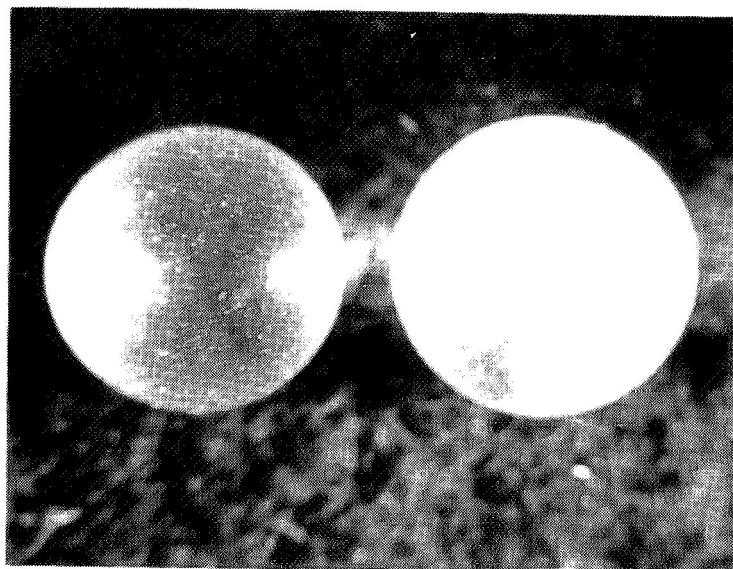


Figure 11. Change in Shape of 4mm Glass Bead After Containless Melting. Melted Bead on Left, Unmelted on Right (9.3X)

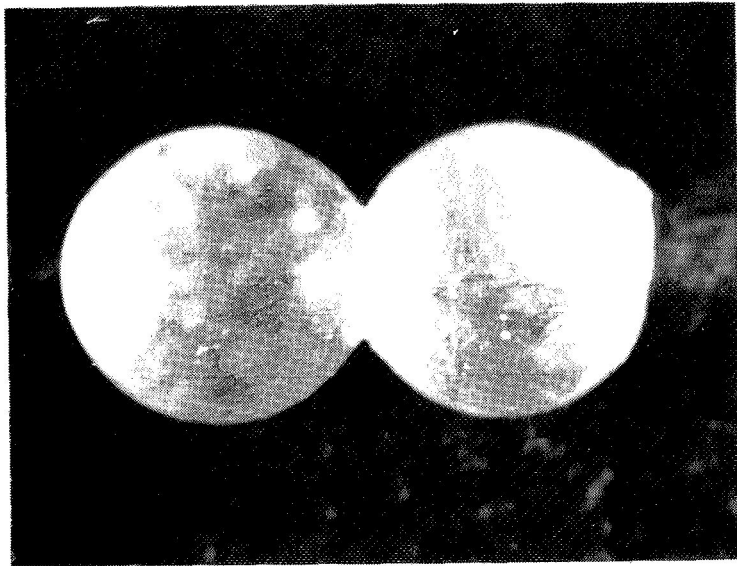
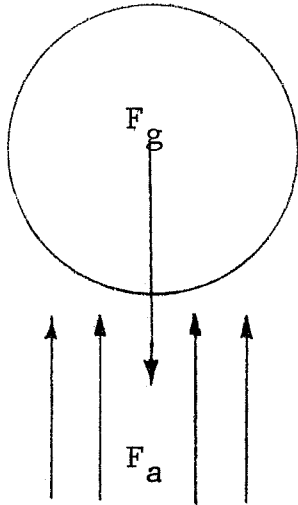
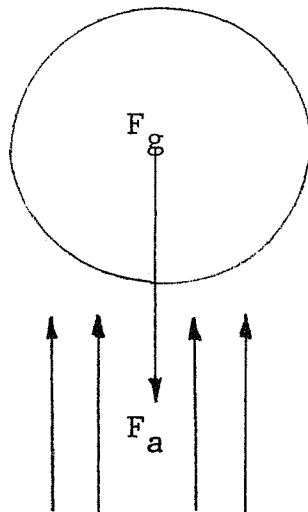


Figure 12. Two 4 mm Glass Beads which Fused Together while Levitated (9.3X)



a. Solid Sphere, $F_a = F_g$



b. Molten Oblate Sphere, $F_a > F_g$

Figure 13. Change in Sphere Shape and Force Equilibrium

monitor the location of the object is necessary to maintain equilibrium.

4.4 Analysis of Results

These encouraging results can be attributed to a fresh approach towards the problem. More emphasis was placed on understanding the relationships between specimen and the levitator. New approaches in acoustical field generation were pursued. Experiments showed that not only is the type of material being levitated important, but that the size, shape and distribution of the specimen are also important. The results show that trade-offs exist between levitations force, F_a , and stability which can be affected by the levitator input current, reflector distance and the reflector material. By carefully studying these variables and the physical properties of the specimens, methods of producing stable levitations were developed.

A three step process was followed for each material. The first step was to achieve stable levitation in free surroundings. Once this was done the remaining steps were easier since a set of operating parameters were then at hand. The second step was to achieve stable levitation in a cold furnace cavity. The third and final step was to achieve stable levitation in a heated furnace.

Experimentation with a heated furnace has shown that the starting shape of the specimen becomes more important, since materials contract when their melting temperatures are approached. This means that easily suspended shapes such as discs and thin squares begin to deform randomly to the point where the field can no longer support them. Conversely a sphere tends to hold its original shape and even after melting could be cooled within the acoustical field without losing its shape or suspendability. A sphere also can be stabilized by rotation which can be induced and maintained on the specimen by judicious control of the input current.

5.0 CONCLUSIONS AND RECOMMENDED WORK

After development on this program, the acoustic levitation apparatus which was supplied to IITRI is now capable of stable levitation of small objects for long periods of time at room temperature. The most stable shape to levitate is the sphere since its sectional density is constant for any orientation. Further work is required to develop techniques and apparatus for stable high temperature levitation and melting.

The overall process of developing and conducting a successful in-space containerless materials processing experiment involves the engineering and science and art of the experiment itself, and of the acoustic position control system used. The purpose of the present ground-based program on the production of infrared-transmitting chalcogenide glasses was to integrate the acoustic levitation system with the glass processing experiment so that specific procedures, equipment, techniques, etc. could be developed. However, the Intersonics/MSFC system that was supplied to IITRI did not possess the long term, 1-g, controllable, high-temperature stability required by the processing experiment.

Clearly, the art and science of acoustic levitation must be more highly developed, and integrated into the experiment package by acousticians and ceramicists working closely together in an interdisciplinary program. Present-day acoustic position control devices are not simply like an oven that the experimenter confidently turns on to reach the desired environmental condition, i.e. temperature. The environmental condition of containerlessness in a 1-g atmosphere is much more closely linked to the experiment itself, especially for an experiment consisting of compounding materials at elevated temperatures. Therefore, for such a complex in-space experiment to be successful, the acoustic position control technology must be developed concurrently and in conjunction with the ceramics processing technology.

IITRI's recommendation for future work, therefore, is to establish such an interdisciplinary program under the guidance and leadership of one principal investigation, in order to develop the acoustic and ceramic processing technologies involved. In this manner the overall procedures and equipment can be developed on earth that will insure the success of future in-space processing experiments. It must be emphasized here that 1-g levitations developed in such a program will not be like 10^{-5} -g levitators. The development of a suitable 1-g device, however, will have the interesting possibility for spinoff to many potential earth-bound applications.

APPENDIX

"Observations on the Operation of the Acoustic Levitator"

S. W. Schramm

A) Start up

The following procedure has been followed religiously through out the testing program and may be considered the reason for the extended success of the project. These steps assume starting with none of the equipment operating.

- 1) Put on ear protective devices.
- 2) Turn on oscilloscope power switch.
- 3) Turn air valve to wide open.
- 4) Turn water on so a steady stream can be seen from the hose exit and slow dripping occurs at the fitting.
- 5) Check to see if amplifier gain is at its lowest position, magnet power switch is off and amplifier level switch is on low.
- 6) Turn main power switch on.
- 7) Wait two minutes.
- 8) Turn magnet power switch on.
- 9) Wait one minute.
- 10) Turn microphone switch on.
- 11) Turn amplifier gain knob until a one amp change occurs on the ammeter and wait thirty seconds.
- 12) Repeat step 11 until five amps is reached.
- 13) When five amps is reached continue step 11 except allow one minute before turning gain control.
- 14) When desired ammeter value is reached wait two minutes before inserting specimen to allow the accoustical field to stabilize.

If the unit is going to be used repeatedly but not constantly during the day the following may be done;

- 1) Turn gain control to zero (counterclockwise)
- 2) Turn magnet switch off
- 3) Keep main power on and air and water flowing.

The air and water cool the unit while keeping the main power on assures a more stable field since electrical connections are not repeatedly broken,

B) Shutdown

Since heat is built up during the accoustical process the shutdown procedure is critical to the equipment;

- 1) Turn gain control to zero
- 2) Turn magnet switch off
- 3) Turn main power microphone and oscilloscope off
- 4) Keep air and water flowing for a minimum of five minutes (at least double that when furnace is used).
- 5) Double check switches and close valves.

Generally the air and water were allowed to flow until the piston could be handled with bare hands.

C) Reflectors

- 1) Materials;

Because the reflector is required to withstand a high temperature and not deform a wide range of materials from brick to metal were tried. The following have been successfully used as reflectors; 1/2" thick fused quartz

in single and double layers, 1/4" thick stainless steel plate and four different types of hard firebrick. The common denominator was hardness. A porous K-28 firebrick was tried but failed because the accoustical pressure was large enough to bore out the brick material.

2) Positioning;

The strength and stability of an accoustical field was found to be very reflector position sensitive. So much so, that if high input currents were used the reflector had to be securely clamped because vibration of the reflector would cause the field to deteriorate.

3) High Temperatures;

If a corresponding material could be found, the reflector could also serve as the cover brick for the furnace cavity. In this configuration the reflector's relationship to the piston was more critical because it had a tendency not to be parallel to the piston surface. This would cause weakened and wandering nodes to appear. In the last experiments the combined reflector cover was dropped because of heat absorption effects. If the brick was a good reflector it was a poor insulator for the furnace and caused a cool spot to exist at the specimen suspension position. This meant high temperatures were nearly impossible to achieve at the node.

A) Field Tuning;

Once the reflector is positioned correctly above the piston, the accoustical field may be fine tuned using an oscilloscope and a microphone. This procedure tends to be more effective in a free air situation as the presence of the furnace acts as a sound insulator.

A microphone placement position was marked and used repeatedly, although this is not necessary because tuning is done by relative amplitudes. The object is to get the highest amplitude for a given input current by adjusting the distance between the piston and reflector. This should correspond to one of the many resonant positions.

In addition to showing the best reflective distance, the oscilloscope trace also indicats the steadiness of the field.

E) Pistons

A group of four pistons were available for use throughout the testing period. Of these, only numbers one and two were used consistantly.

It was not unusual for the pistons to become very hot on the long duration runs; hence, the two were used interchangibly.

They were always allowed to cool in place before substitution. Surface scaring was often caused by specimens bouncing between piston and reflector.

F) Field Effects;

The field can be moved through space intact with a specimen within it. An arrangement was devised so that the piston and reflector could be moved in unison during operation. During one test over ten specimens were moved through a six inch vertical displacement without disruption.

The sound pressure field also shows signs of being moderately flexible. A cantilever reflector was being used and it was found that the field acts much like a spring. If the reflector was pulled up slightly the specimens would move up in a fashion much like the coils of a bottom-secured spring. The upper specimens would extend farther than the lower ones. A similar thing occurred upon compression of the reflector.

The acoustical field is also sensitive to its surroundings. During reflector experiments attempts were made using a quartz cylinder around the field. This was found to badly disrupt the formation of the standing wave. No specimens could be suspended in the tube as they were immediately forced towards the tube wall. This same sort of attraction occurred when a helical wire coil was placed within the field.

This does not mean that the presence of an object in the field necessarily disrupts the field. A wire mesh screen can be passed through the field without reducing the suspension. In fact a wire screen was successfully used as a heat reflector during the furnace experiments.

The furnace experiments also showed that the stability of the field is temperature dependent. As the furnace temperature is increased and the density of the working gas changes, less input current is required to maintain a suspension as compared to room temperature. This was observed using both the furnace and heating coil.

Specimens within the field can be affected by using the gain control in various ways. When the gain is increased beyond the point of stable suspension rotation can be induced and controlled. This may be of use in the processing of large numbers of specimens simultaneously. The gain control can also be used to control oscillation in both the horizontal and vertical planes.

One phenomenon which was repeatedly seen during multiple levitations is the existence of a static effect whereby clusters of specimens tend to act as one body. Also a specimen of one material which could not levitate on its own can levitate successfully in conjunction with a specimen of another material which levitates alone. An example of this glass and styrofoam is spheres at low power.

In general, the best node in which to suspend specimens for long periods most stably is the first node under the reflector.

G) Heating:

As was mentioned earlier the presence of heat changes the power requirements for the field. Its presence also can be disruptive to the field if added too quickly.

It was found that the rapid addition of heat to a furnace cavity caused transient convection currents to form. The intensity of these currents was great enough to knock specimens out of their suspending nodes.

To minimize this effect a particular sequence was developed for in-furnace melting. This furnace is heated to just below the expected melting temperature before the field is established and the specimen entered. Once the specimen is stable the heat is slowly added until the melting temperature is reached. This was far more satisfactory than attempting to raise the furnace temperature while suspending the specimen in the field.