DEVELOPMENT OF A DEVICE TO DEPLOY FLUID DROPLETS IN MICROGRAVITY

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SUMMARY

A free-floating droplet in microgravity is ideal for scientific observation since it is free of confounding factors such as wetting and nonsymmetrical heat transfer introduced by contact with surfaces. However, the technology to reliably deploy in microgravity has not yet been developed. In some recent fluid deployment experiments, droplets are either shaken off the dispenser or the dispenser is quickly retracted from the droplet. These solutions impart random residual motion to deployed droplet, which can be undesirable for certain investigations. In the present study, two new types of droplet injectors were built and tested. Testing of the droplet injectors consisted of neutral buoyancy tank tests, 5-sec drop tower tests at the NASA Lewis Zero Gravity Facility, and DC-9 tests. One type, the concentric injector, worked well in the neutral buoyancy tank did not do well in low-gravity. However, it appeared that it makes a fine apparatus for constructing bubbles in low-gravity conditions. The other type, the T-injector, showed the most promise for future development. In both neutral buoyancy and DC-9 tests, water droplets were formed and deployed with some control and repeatability, although in low-gravity the residual velocities were higher than desirable. Based on our observations, further refinements are suggested for future development work.

1. INTRODUCTION

1.1 Problem

A free-floating droplet in microgravity is ideal for scientific observation since it is free of confounding factors such as wetting and non-symmetrical heat transfer introduced by contact with surfaces. As simple as it may sound, the technology to deploy a stationary free-floating droplet in microgravity has not yet been developed. The difficulty arises in overcoming the forces on the droplet caused by surface tension, and wetting as the droplet detaches from the dispenser without any velocity. In recent fluid deployment experiments, droplets are either shaken off the dispenser or the dispenser is quickly retracted from the droplet. These solutions impart random residual motion to the fluid which can be undesirable for certain investigations.

Dr. An-Ti Chai of the Microgravity Fluids Branch at the NASA Lewis Research Center developed two different types of droplet injectors that may eventually lead to a better deployment solution. The goal was to develop a device with the ability to deploy droplets in microgravity with an acceptably low velocity. The velocity should be on the order of a few millimeters per second. Such a droplet could remain within view of video and diagnostic systems for sufficient time to satisfy the needs of many fluid researchers.

This paper documents the work performed to date at NASA Lewis Research Center on the attempts to develop a new method of deploying free floating liquid droplets for future microgravity-based fluids experiments.

1.2 Previous Work and Current Solutions

Single Needle

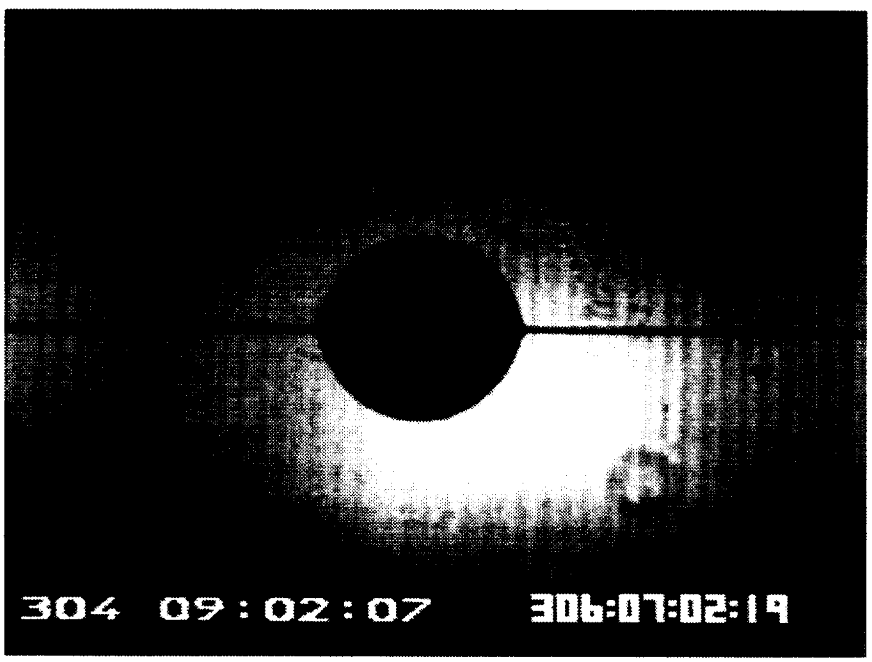
Experimenters have developed several ways to deploy liquids in microgravity. Perhaps the most common solution is to form a droplet with a syringe and needle. When the droplet is of sufficient size, the needle is quickly retracted or "snapped back" from the droplet. Since the adhesion of the fluid to the needle is small relative to the inertia of the droplet, the needle pulls away from the droplet and the droplet is left free floating; however, there is a velocity imparted to the fluid. The direction of fluid motion is generally towards the needle, but the speed is random from deployment to deployment and can be unacceptably high for some applications.

Opposing Needles

To resolve the problem of a directional force being imparted to the droplet by the retracting needle, researchers have employed a dual-needle concept. The NASA Lewis Droplet Combustion Experiment uses this approach. Two needle tips or thin dispenser tubes are brought together and slowly backed away from each other as the droplet forms between them. For deployment, the needles are simultaneously snapped back in opposite directions and equal speed. Theoretically, this creates equal and opposite forces which cancel out and eliminate movement of the free-floating fluid.

Actual tests in microgravity show that the fluid has more attraction to one needle than the other so that the resulting deployment is even more unpredictable than with a single needle. The droplet can move either towards one needle or the other, and the resulting velocity was unpredictable. However, experience has shown that a certain percentage of deployments have acceptably low velocities, and this method has been used successfully on several microgravity experiments.

An enhancement to the dual-needle design is to use a thin fiber as a support for the droplet. The droplet is formed on the fiber which provides an "anchor" to prevent the droplet from moving when the needles are retracted. The disadvantage to this solution is, of course, that the droplet is no longer free floating and has a foreign object through it which causes nonideal effects such as non-spherical symmetry of heat transfer and deformation of the free surface. These effects can be minimized by using a fiber with low heat conductivity and a fluid with high surface tension and low attraction to the fiber.



8 mm diameter fluid droplet in microgravity suspended on a fiber support.

Acoustic Levitation

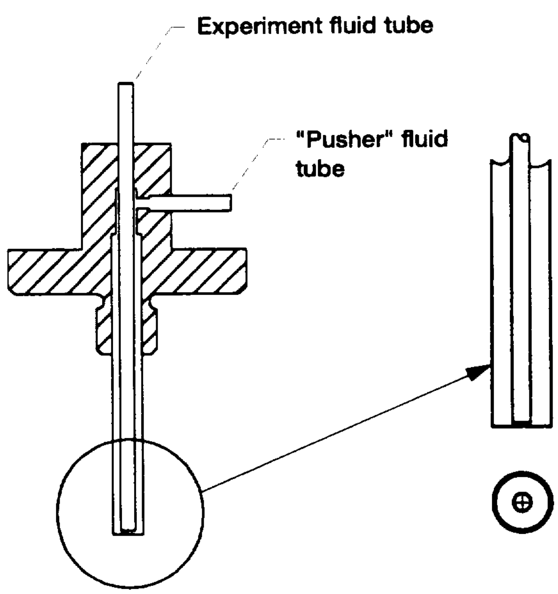
Another solution that works well for many researchers is to use an acoustic levitation device which holds the droplet in the gentle grip of sound waves. The Fluids Module developed at JPL and flown aboard USML-2 in 1995 utilized this type of device for several investigations. A disadvantage of this solution is that the sound waves can disturb the fluid free surface, a feature that may not be acceptable for all types of investigations. Another disadvantage that the levitator device requires more resources, such as mass, volume, and money than other devices.

2. DROPLET INJECTOR DESIGN

Two unique kinds of droplet deployment devices (referred to as "droplet injectors") were designed, built, and tested at NASA Lewis in 1995. The principle that both kinds of injectors employ is to use a nonwetting fluid to push an "experiment" fluid off of the injector tip in a controlled and repeatable manner. Two mutually nonwetting immiscible fluids such as oil and water will ideally not have any attractive forces between each other. The "pusher fluid" will be a neutral agent which exerts force to separate the experiment fluid from the injector device, thus allowing the experiment fluid to float free.

2.1 Concentric Injector

2.1.1 Description.—The first droplet injector concept developed was dubbed a "concentric" injector. It can be described as a tube within a tube. The inner tube contains the experiment fluid to be deployed and the outer tube contains the immiscible "pusher fluid." Syringes connected to the tube provide the force for fluid formation and deployment. Drawing 1 illustrates the concentric injector.



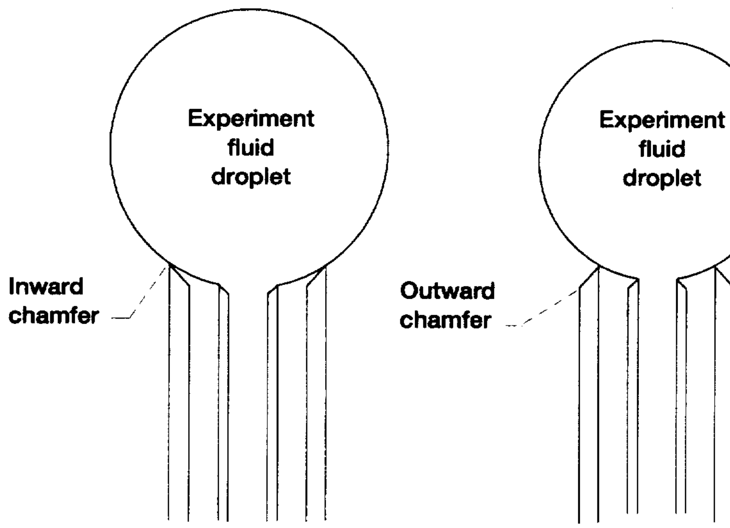
Concentric injector design

Drawing 1. Concentric injector design.

The injector tubes were fabricated from 300-series stainless steel tubing and the body was made of aluminum. The tubes were mounted into the injector body via epoxy.

The desired operation in microgravity is as follows. As the experiment fluid syringe plunger is depressed, a droplet begins to form on the tip of the inner tube. Once the droplet reaches the desired size, the pusher fluid syringe plunger is depressed slowly. The pusher fluid exerts pressure on the experiment droplet, separating the droplet from the rim of the injector tip. The droplet, free from the injector tip, begins to free float with a very small velocity.

2.1.2 Methods to Reduce Fluid Attraction to the Injector Tip.—The attraction of the experiment fluid to the injector tip can be minimized by reducing the surface area of the tip that the fluid contacts. This is accomplished by chamfering the tip to a sharp edge. The 1A injector had the edge of the tube tips chamfered angled such that the droplet balanced on the thin edge with very little contact area. An analogy would be to balance a marble on the end of a drinking straw. The 3A injector was designed with the interior of the tip chamfered such that the tip was flared. Drawing 2 illustrates the two kinds of chamfers.



Droplet injector tip chamfers.

Drawing 2. Droplet injector tip chambers.

To further reduce the attraction of the experiment fluids to the tip of the injector, a nonwetting barrier coating was applied. The coating was 3M FC-722. According to the manufacturer, this coating provides a thin low-energy surface which is nonwetting to water and some other liquids. Unfortunately, the coating is easily rubbed off metal surfaces and is not nonwetting to solvents such as Freon. A more durable nonwetting coating would be desirable in future projects.

2.1.3 Tube Diameters.—One factor that affects deployment is the ratio of diameters of inner and outer tubes. If the outer tube diameter is too large relative to the inner tube, then the pusher fluid will not be able to separate the experiment fluid from the tip. The size of both tubes also determines the minimum and maximum size of a deployable droplet.

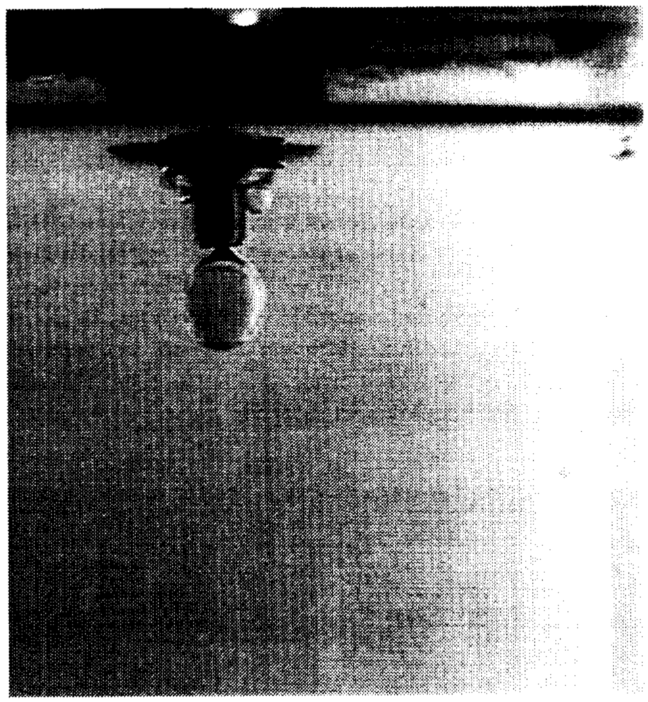
Seven droplet injectors were fabricated having different inner and outer tube diameters. The ratio of inner to outer diameters was chosen to encompass a reasonable range. The following chart details the dimensions of the injectors:

TABLE 2.1.—CONCENTRIC INJECTOR TUBE DIMENSIONS

Injector	Inner tube OD, in.	Inner tube ID	Outer tube OD	Outer tube ID
1A	0.0625	0.044	0.156	0.116
1B	.0625	.044	.187	.1476
2A	.125	.089	.250	.180
2B	.125	.089	.250	.222
3A	.125	.089	.187	.147
DGS	.020	.016	.062	.044
DGL	.0625	.044	.125	.089

2.2 T-Injector Description

Another kind of droplet injector was built and tested which came to be called a "T-injector." The concept of the T-injector consists of having two tubes merge into one tube. The intersection of tubes forms a "T." Drawing 3 shows the T-injector design.



'iew of the droplet showing the "neck formation effect" prior to

The tubes are made of 300-series stainless steel and the body is made of aluminum. Epoxy secures the tubes into the injector body.

The injector is operated by forming a droplet of the experiment fluid onto the tip. Then the immiscible pusher fluid (typically air) is slowly forced out to form a slug or bubble in the experiment fluid tube near the tip. Continued pushing would detach the experiment droplet off the tip and presumably into the air at a low velocity.

To reduce attraction of the fluid to the tip, it was convenient to install a Teflon tube onto the injector. Teflon is nonwetting to water and many other fluids so the attraction of fluids to the Teflon should be very low. The tip of the Teflon tube was slightly flared.

3. INJECTOR TESTING

A series of tests was performed on the droplet injectors to determine how effective they were at deploying droplets. Neutral buoyancy testing was performed in the laboratory. Later, drop tower testing was performed in the NASA Lewis Zero Gravity Facility, followed by a series of low-gravity tests on the DC-9.

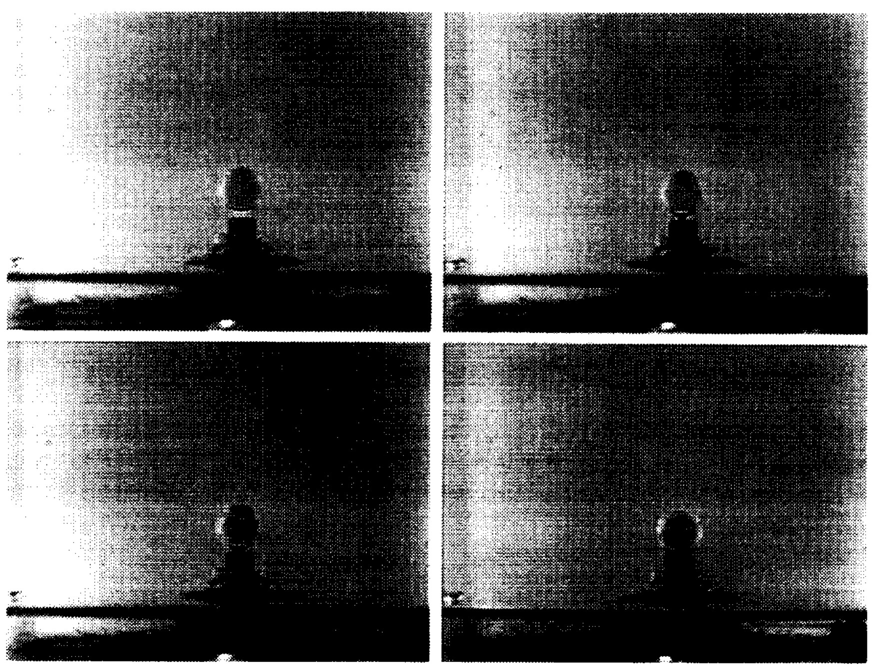
3.1 Neutral Buoyancy Tests

Neutral buoyancy tests were a very convenient and inexpensive way to perform an initial evaluation of the droplet injectors. The state of neutral buoyancy can be achieved by matching densities of the host (ambient) fluid and the experiment fluid. If the fluids are immiscible, then no diffusion or mixing will occur. When the densities match, the experiment fluid will neither rise nor sink in the host fluid. This simulates some aspects of zero-g since the effect of gravity is canceled out by the buoyancy of the experiment fluid in the host fluid. Not all aspects of zero-g are simulated, for instance, the viscous host fluid which damps the initial velocity of the deployed droplet or bubble, would not have to be dealt with in low-g environment.

From previous experience, it was known that glycol and water (commonly used as anti-freeze) could be mixed in a ratio to match the density of Dow Corning 705 diffusion pump oil. Since these fluids are immiscible this combination is convenient.

3.1.1 Setup and Apparatus.—For the neutral buoyancy tank tests, a transparent acrylic tank was filled with diffusion pump oil. A plate containing a hole large enough to fit the droplet injector tip was fabricated. This plate was bolted onto the top of the tank. The experiment fluid was a mixture of glycol, water, and red food coloring which was empirically mixed until its density matched that of the Dow Corning 705 diffusion pump oil host fluid. The pusher fluid was also diffusion pump oil. Two commercial motor driven syringe pumps were used to deploy the fluids. The pumps had a maximum dispensing rate of 0.14 mm/sec. A video camera was used to record the results.

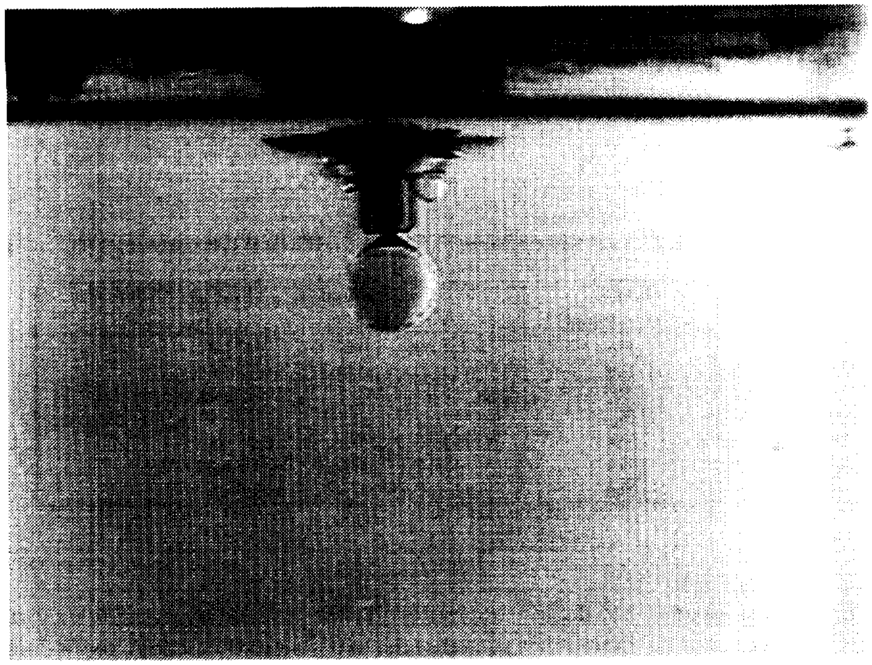
3.1.2 Concentric Injector Testing Results.—Formation of a spherical droplet on the tip of the droplet injector was quite easy. Droplets of up to 3 centimeters in diameter were created. Droplet deployment occurred under certain conditions, but it was not as easy to deploy droplets as predicted. Three effects were seen which prevented easy deployment. The first effect was the "neck formation" caused by the experiment fluid droplet remaining attached to the fluid inside the injector tube. When the pusher fluid (diffusion pump oil) was deployed, the droplet be pushed off the tip up to 2 mm except for a thin "neck" of fluid from inside the injector tube. This neck would pull the droplet back onto the injector tip once the pusher fluid deployment stopped.



Deployment sequence from top left, top right, bottom left, bottom right. Note the "neck" of the droplet seen in bottom left photo. Host fluid is oil, experiment fluid is water/glycol.

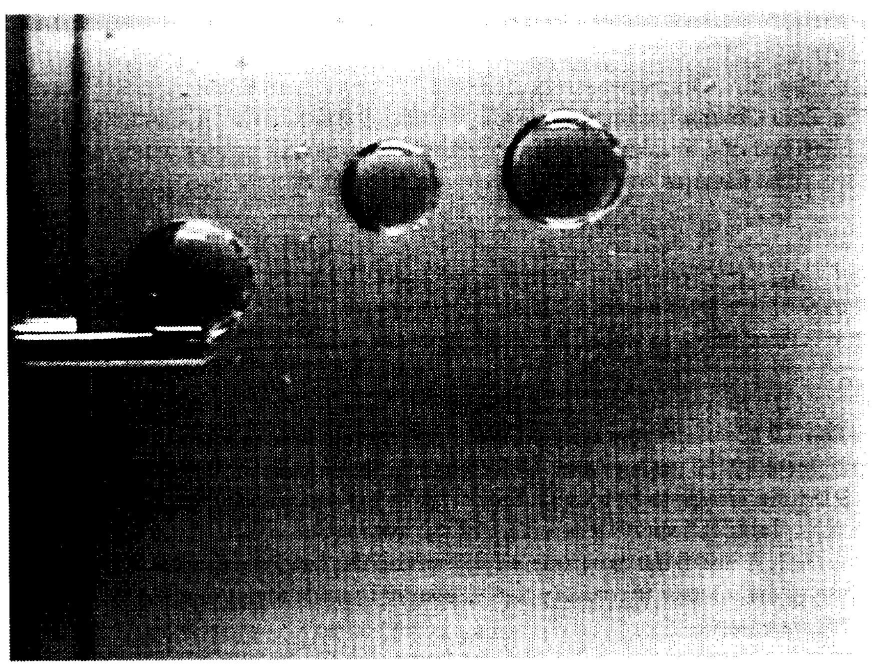
When deployment did occur, it occurred after enough force was imparted by the pusher fluid to separate the experiment droplet far enough from the tip to break the neck of the droplet. Due to viscous damping by the host fluid, the droplet did not move very far or fast from the tip before stopping. In microgravity the deployed droplet would deploy at an undesirable rate.

The second effect seen was the "bubble formation" where the immiscible pusher fluid went inside the experiment fluid droplet instead of around the outside of the droplet. When this occurred, there was no impulse or pushing action and the droplet could not be deployed.



Closeup view of the droplet showing the "neck formation effect" prior to deployment.

The third effect that completely prevented droplet deployment was wetting of the injector by the experiment fluid. Occasionally the stainless steel tube of the injector would become wetted by the experiment fluid. Upon subsequent dispensing, the experiment fluid would not form a droplet but rather wet the side of the tip tube or move back onto the threads of the injector body. The injector had to be periodically cleaned with alcohol to prevent this effect.



One droplet wetting the injector and two successfully deployed droplets. Host fluid is oil, experiment fluid is water/glycol.

Deployment was most efficiently attained at the highest pusher fluid dispensing rate of 0.14 mm/sec. Deployment did not occur at rates lower than about 0.07 mm/sec. Using intermediate dispensing rates required more time and more pusher fluid.

The following table shows the results of the concentric injector neutral buoyancy testing.

TABLE 3.1—RESULTS OF NEUTRAL BUOYANCY TESTING WITH CONCENTRIC INJECTORS

Concentric injector	Able to deploy droplets?	Volume pusher fluid used/dispense rate	Minimum droplet size
1A	Yes	0.08 ml at 0.14 ml/sec	>0.05 ml
1B	Yes	.30 ml at 0.14 ml/sec	>0.05 ml
2A	No	N/A	Unable to deploy droplets
2B	No	N/A	Unable to deploy droplets
3A	Yes	.08 ml at 0.14 ml/sec	>0.05 ml
DGS	Yes	.15 ml at 0.14 ml/sec	>0.05 ml
DGL	Yes	.30 ml at 0.14 ml/sec	>0.05 ml

The 2A and 2B injectors were unable to deploy droplets at all. The problem appeared to be that the outer injector tubes were too large compared to the inner tubes such that the experiment fluid could not be forced out at a high enough rate to push the droplet off the injector tip. The pusher fluid traveled around the experiment droplet without exerting much pushing force.

3.1.3 T-Injector Neutral Buoyancy Testing.—The T-injector was tested in the same manner and with the same fluids as the concentric injector. Droplet formation and deployment occurred with ease. Droplets from 1 mm to 30 mm diameter could be formed and deployed in the tank. The "neck formation" problem encountered with the concentric injectors did not occur due to the different injector geometry. The droplet was held on the tip by small adhesion forces which were easily overcome by the pusher fluid.

3.2 Zero Gravity Facility Drop Tower Tests

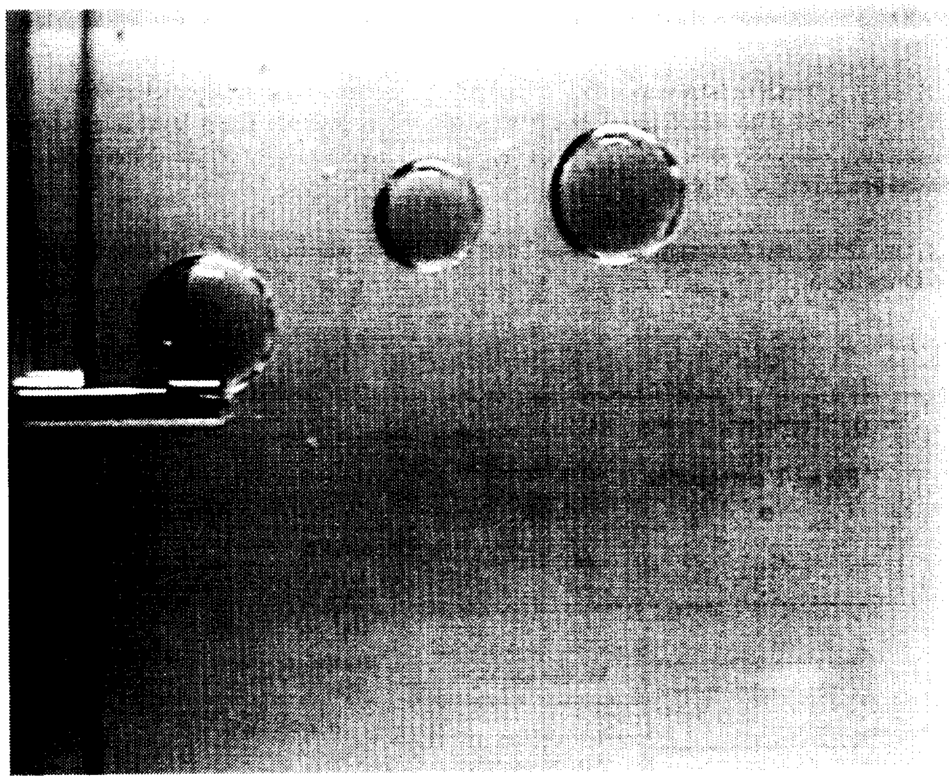
3.2.1 General Description.—Drop tower tests at the NASA Lewis Zero Gravity Facility were performed on both kinds of injectors. The Zero Gravity facility drop tower provides 5.2 sec of 10^{-5} g's. An autonomous test rig was built for the tests. It consisted of a droplet injector connected to two electric pumps which supplied the experiment and pusher fluids. Two video cameras were focused onto the tip of the droplet injector. Drawing 4 details the test rig design.

3.2.2 Selection of Fluid Combinations.—Several experiment fluids and "pusher" fluids were tested. Water was chosen as a baseline experiment fluid because it is cheap and nontoxic. Dow Corning silicone oil was chosen as a pusher fluid because it is immiscible to water. Although air is not a liquid, it is also immiscible to water and was chosen for testing.

3.2.3 Results.—The 5.2 sec of microgravity provided just enough time to form a droplet of about 7 mm in diameter and attempt deployment by the pusher fluid. Unfortunately, facility constraints prevented more than one or two runs per month. DC-9 testing proved to be a much faster way to get data, so the Zero Gravity Facility tests were terminated after five runs. Table 3.2 shows a summary of the test results.

During Run numbers 1, 4, and 5 the experiment fluid wetted the tip of the droplet injector and prevented deployment. Fluid wetting the injector tip usually moves over to the side of the injector tip tube or spreads out in a film across the tube outer wall.

During Run number 2, a droplet of glycol/water was formed on the injector tip. The pusher fluid (oil) pushed the water droplet off the tip but the droplet did not release from the oil despite the fact that glycol/water is immiscible to oil.



One droplet wetting the injector and two successfully deployed droplets. Host fluid is oil, experiment fluid is water/glycol.

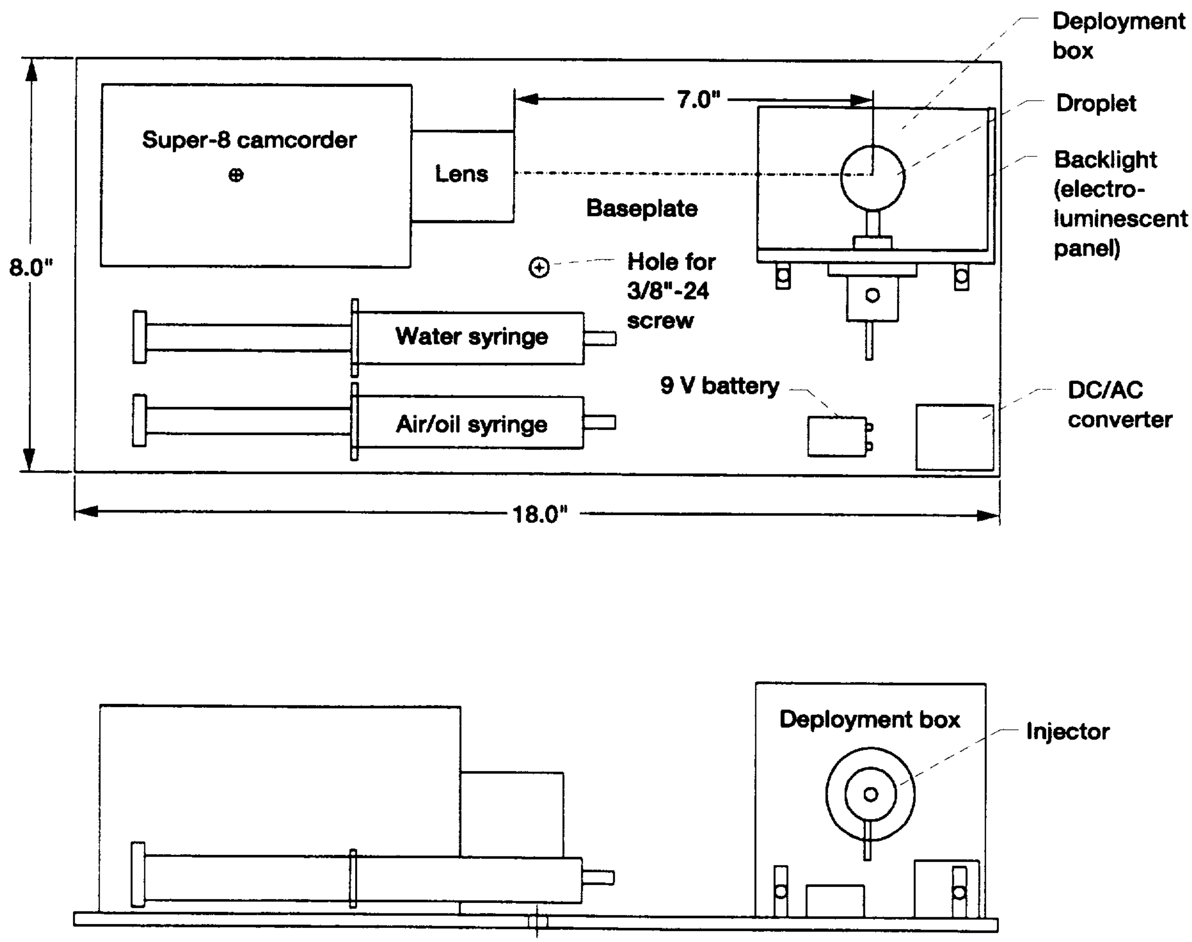
TABLE 3.2—FIVE SECOND DROP TOWER RESULTS

Run number	Injector	Experiment fluid	Pusher fluid and dispensing rate	Results
1	1A	Glycol/water (0.3 ml)	Dow corning 705 pump oil (o.12 ml at 0.14 ml/sec)	Droplet formed and immediately wetted and slumped over to the side of the injector tube
2	1A	Glycol/water (0.3 ml)	Dow corning 705 pump oil (0.12 ml at 0.14 ml/sec)	Droplet formed and was pushed off tip by oil but droplet did not release from the oil
3	1A	1 centistoke silicone oil (0.3 ml)	Air (dispensed at 0.14 ml/sec)	No droplet formation, oil had evaporated in fluid line
4	1A	10 centistoke silicone oil (0.3 ml)	Air (dispensed at 0.14 ml/sec)	Oil droplet formed but wetted the injector tube and slumped over to the side of the tube
5	T, with Teflon tip	Pure water (0.3 ml)	Air (dispensed at 0.14 ml/sec)	Droplet immediately wetted Teflon tip and did not form droplet

3.3 Injector Tests on the Low Gravity DC-9

DC-9 testing proved to be a very efficient and effective way to test the droplet injectors. The NASA Lewis DC-9 flies a parabolic path which provides up to 20 sec of low gravity. The g-level fluctuates during each parabola but averages approximately 0.01 g. Some parabolas have a higher quality of low-g than others. Typically up to 45 parabolas are flown per flight.

3.3.1 Test Setup and Apparatus.—A small manual test rig was built and bolted to the floor of the DC-9, as shown in Drawing 5.



Drawing 5. DC-9 test rig.

The test rig consisted of a metal plate with two syringes, a Hi 8mm video camera, and a square metal containment box bolted onto it. The metal box was a five-sided cube with the open side facing the camera. A 9V battery operated an electroluminescent panel which was taped to the inside face of the cube facing the camera. The droplet injector was fitted through a hole in the side of the metal cube and bolted in place.

The Sony Handicam Super Hi 8mm camcorder received power from DC-9 utilities. The camcorder lens was zoomed in on the injector tip, and the image received was of high quality, clear and without vibration. The electroluminescent panel backlighting was not necessary, but post-flight analysis showed that it was more desirable as it provided a better silhouette of the droplet.

A 0.063 in. thick Lexan square was cut to size and fit over the open end of the containment box via Velcro tabs to provide containment of the experiment fluids during flight. This window was easily removed between runs to allow the operator to wipe off or change up the injector.

During the flight of the DC-9, the camcorder and electroluminescent panel were turned on. When the DC-9 reached microgravity levels, the plunger on the experiment fluid syringe was depressed slowly. The test operator observed the formation of a droplet on the injector tip. When the droplet was of sufficient size (1-2 cm diameter), the plunger on the immiscible "pusher" fluid syringe was depressed slowly to deploy the droplet. During the 2-g pullup maneuver, the rig was readied for another run. Both the concentric and T-injectors were tested on three DC-9 flights.

3.3.2 Selection of Fluid Combinations.—In addition to water, silicone oil, and air (cf. Section 3.2.2), Freon 113 and Ethyl Alcohol were also chosen for experiment fluids because they are relatively safe to use on the DC-9 but have different properties (such as surface tension) than water. In many cases, more than one trial was possible per DC-9 parabola.

3.3.3 Results.—Numerous trials were completed during DC-9 flight testing. Some success was seen in deploying droplets, although in no case was a droplet formed and deployed with suitably low velocity. The T-injector was much more effective at forming and deploying droplets than the concentric injector. Table 3.3 provides a summary of the results.

TABLE 3.3—DC-9 DROPLET INJECTOR TEST RESULTS

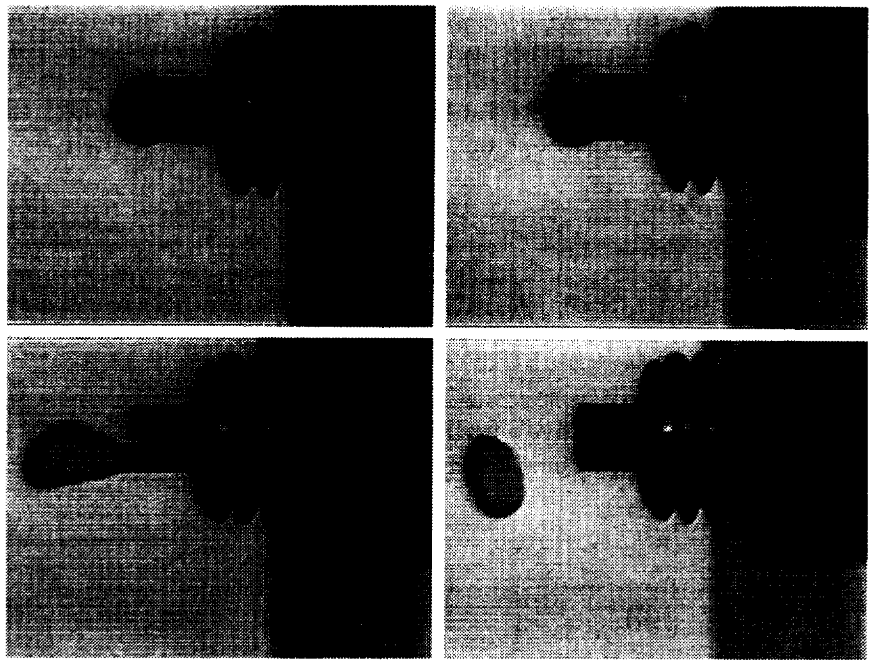
Injector	Experiment fluid	"Pusher" fluid	Number of Trials	Successful deployments?
1A	Water	Air	22	No: created bubbles
1A	Water	Dow corning 10-centistoke silicone oil	6	No: wetting and adhesion of water to oil
1A	Freon 113	Air	8	No: wetting
3A	Ethyl alcohol	Air	11	Yes: 2 partial deployments at high velocity
3A	Water	Air	13	Partial: 1 deployment, the remainder just created bubbles
T	Water	Air	5	No: wetting
T+ Teflon tip	Water	Air	65	Yes: many deployments at velocities ranging from 1.3 cm/sec to 10 cm/sec
T+ Teflon tip	Water	Oil	1	No: oil wetted Teflon
T+ Teflon tip	Freon 113	Air	2	No: Freon wetted Teflon
T+ Teflon tip	Ethyl alcohol	Air	5	No: Alcohol wetted Teflon

3.3.4 Discussion of Concentric Injector Results.—The concentric injector was not very effective at deploying droplets. Typically either the experiment fluid or pusher fluid wetted the injector tip or the pusher fluid entered the droplet and formed a bubble. One water droplet was deployed with the 3A concentric injector. The deployment sequence is shown in photo 5.

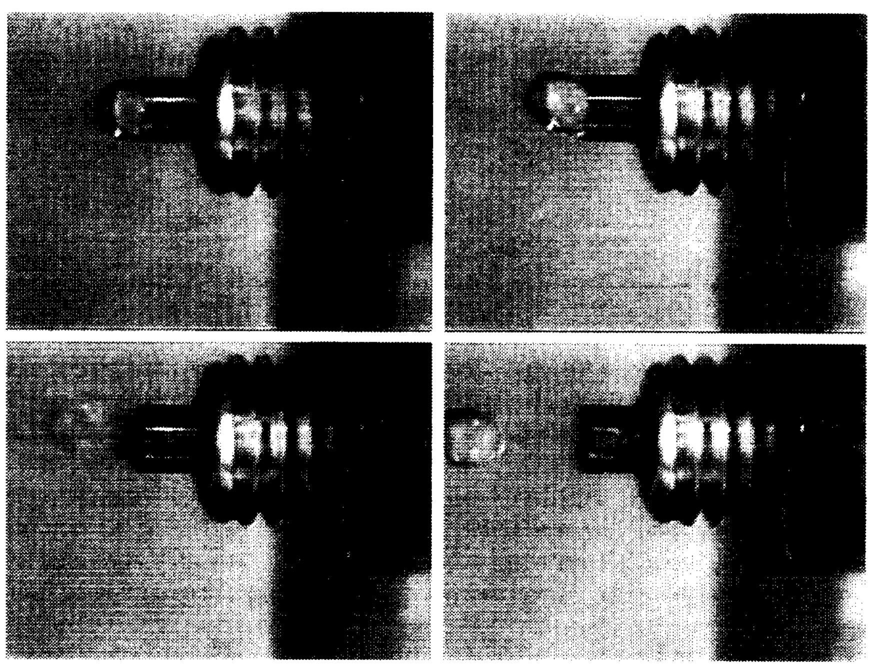
Partial success occurred during a trial with the concentric injector when a six millimeter droplet of ethyl alcohol formed and was deployed by air at about five centimeters per second (Photo 6). During the next trial, a three millimeter diameter droplet of alcohol was deployed when a five millimeter diameter droplet formed on the tip and broke into two pieces due to violent shaking of the droplet as the air passed around it. The deploying droplet moved rapidly away from the tip.

The largest problem appeared to be wetting of the tip by the experiment or pusher fluid. Freon 113 wetted the injector tip in all attempts. Silicone oil wetted the injector tip most of the time, and water wetted the tip a few times (Photo 7). The tip had been coated with 3M FC-722 barrier coating which should have been nonwetting to silicone oil and water, but this coating may have been rubbed off during prior testing. Usually the wetting fluid would not form a droplet on the tip of the injector but would flow over the outer surface of the tube in a film or thin sheet.

The other problem experienced with the concentric injector was the formation of bubbles. Droplets of water of approximately 1 cm in diameter were easily formed on the injector tip, but when the air was deployed, it would

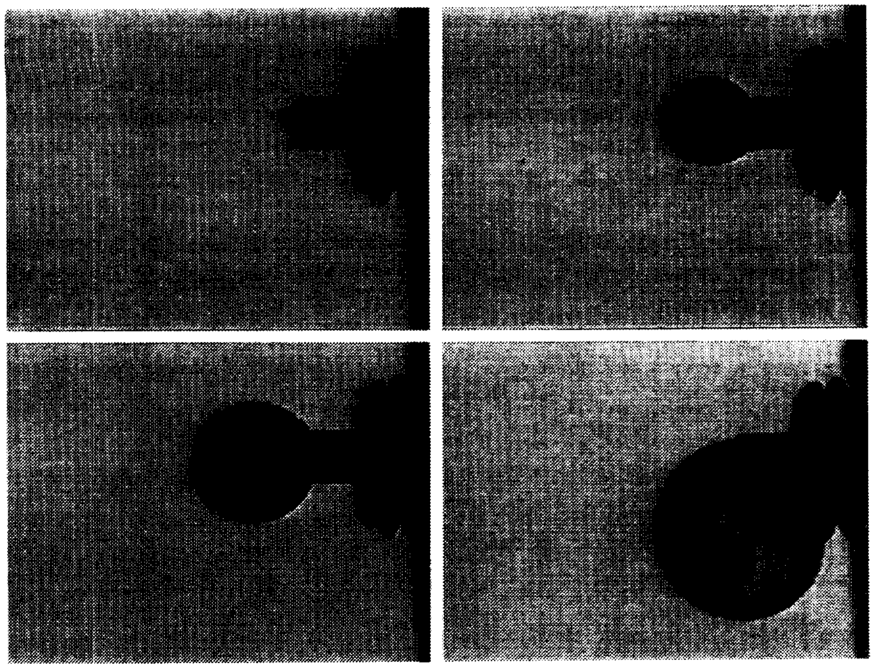


Deployment of water droplet with the 3A concentric injector. Sequence is from left to right. Note the severe vibration and deformation of the droplet due to air passing around and through it prior to deployment. Droplet diameter is 8 mm and deployment velocity is approximately 10 cm/sec.

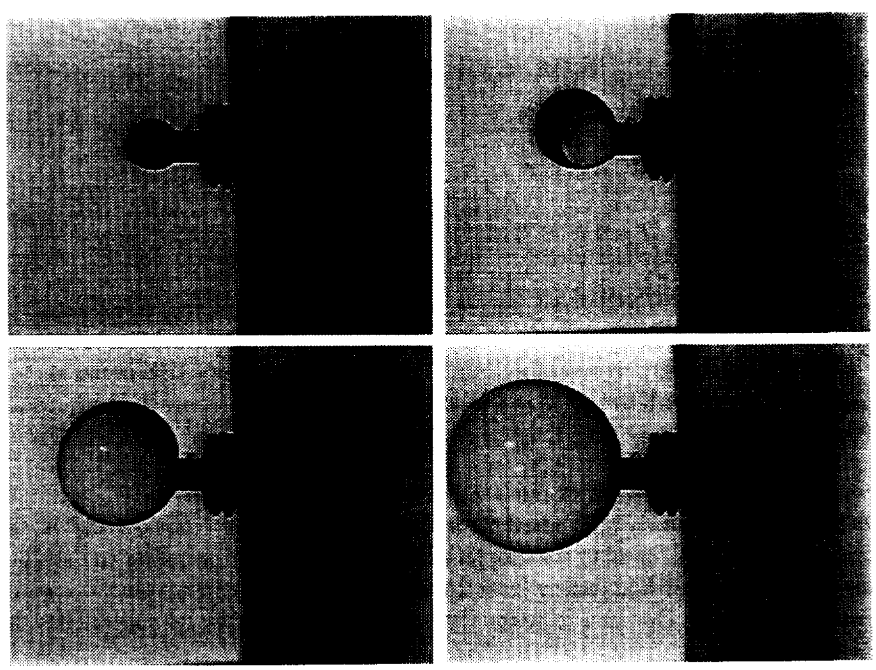


Deployment sequence of 6 mm diameter alcohol droplet on 3A injector.

travel into the water droplet, forming a bubble as shown in Photo 8. Bubbles of 4 or 5 cm in diameter were formed in some cases. The bubble adhered to the injector tip and would not deploy. This also occurred when silicone oil was the pusher fluid.



Water droplet forms and wets the injector tube.



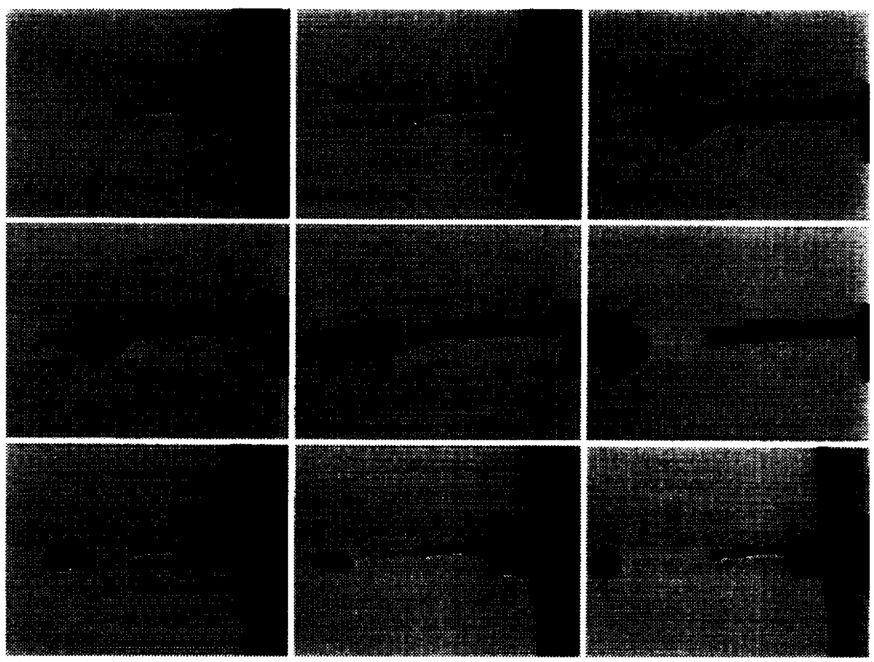
15 mm diameter water droplet forms on concentric injector tip. Air deploys into the center of the droplet creating a spherical "shell" of approximately 36 mm diameter.

A few times, the water droplet was to be pushed off of the injector tip by the oil, but the water droplet would not separate from the oil which was also detached from the injector tip. Obviously the pushing process has to be refined to achieve the intended effect.

The fluctuating gravity levels on the DC-9 tests occasionally caused problems during testing. During a typical parabola, the g-levels fluctuate from about +0.05 to –0.05 g and usually hover in the 0.01 g range. This fluctuating gravity level caused some body forces on droplets which deformed them and prevented droplets larger than about 1 cm in diameter from forming on the injector tip. Droplets larger than about 1 cm tended to roll off the tip of the 1A injector. Using the 3A injector with the reversed chamfer, the droplet contacted more surface area and was more stable. More stability allowed more time for the operator to observe droplet formation and actuate the pusher fluid.

3.3.5 Discussion of T-injector Results.—The T-injector appeared to be better suited at deploying droplets than the concentric injector. Some success in deploying water droplets with air was observed. Droplet sizes were usually in then range of 5 to 7 mm in diameter.

Deployment of water droplets with air was fairly easy to accomplish using the T-injector with the Teflon tip installed. Many droplets ranging from 1 mm diameter to 7 mm diameter were deployed (See Photo 9).

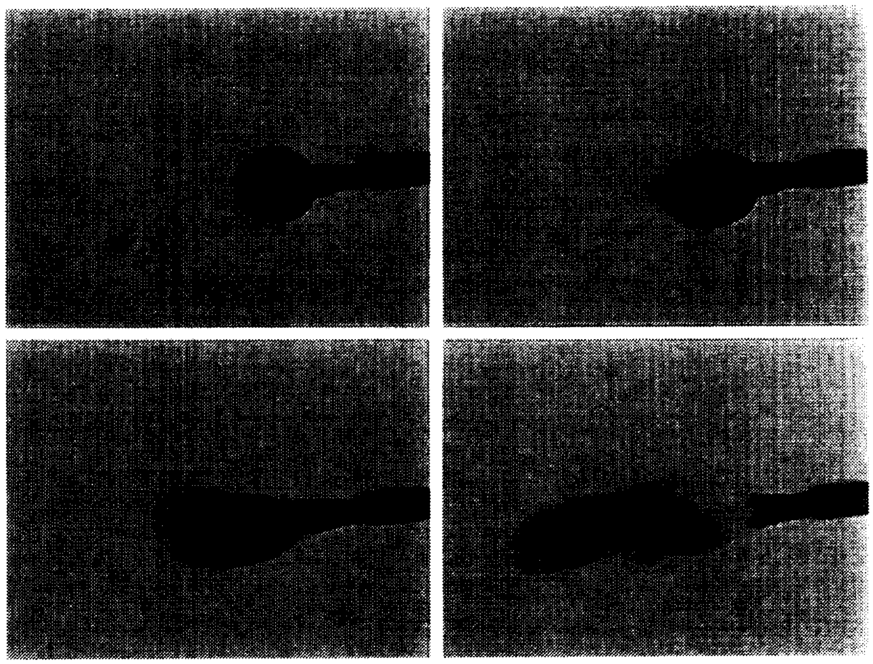


Formation of 7 mm water droplet on T-injector with Teflon tip. Note the air slug passing through and exiting the droplet in middle left photo. This impluse pulls the droplet off the tip at about 5cm/sec velocity.

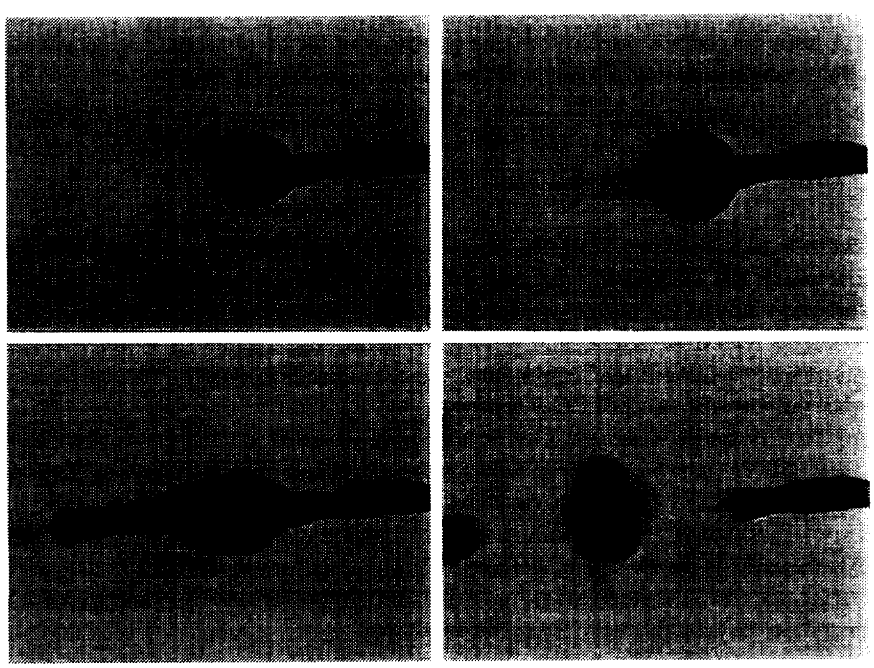
Several things became clear upon review of the test videotapes. Deployment of the water droplets appeared to occur when a slug of air was sent at fairly high speed through the water droplet. Upon exiting the far side of the droplet, enough momentum was transferred to the droplet to cause a violent deformation and shaking to occur. If the momentum was enough, the droplet would deploy from the tip. Typical deployment velocities were higher than desired and ranged from 1 to 5 cm/sec. Operator technique appeared to be primarily responsible for the difference in velocities.

It is likely that improved operator technique could probably reduce the average deployment velocity, although it is not likely that deployments on the order of 1 mm per second could be achieved. Deployment occurs from a pulling action as the air slug exits the far side of the droplet rather than the predicted pushing motion at the droplet to tip interface. The droplet is rapidly deforming (Photo 10) and oscillating (20 to 30 ms/oscillation) due to the air disturbances. Several times a water droplet was observed to detach from the tip upon deformation but reattach on the first or second oscillation as the droplet "rebounded."

The droplet deforms longitudinally (along the centerline of the tip tube, see Photo 11) as much as two times its diameter when the air slug exits the far side. If the center of gravity of the droplet has not moved far enough away from its original position within 20 to 30 ms, then the droplet reattaches itself the tip upon the next oscillation. The droplet center of gravity usually had to move more than 1 mm away from the tip to prevent reattachment. The oscillations limit the minimum droplet deployment velocity in proportion to the frequency of oscillation. If the droplet oscillates at 40 Hz, it will have to move twice as quickly from the injector than if it oscillated at 20 Hz in order to prevent reattachment.

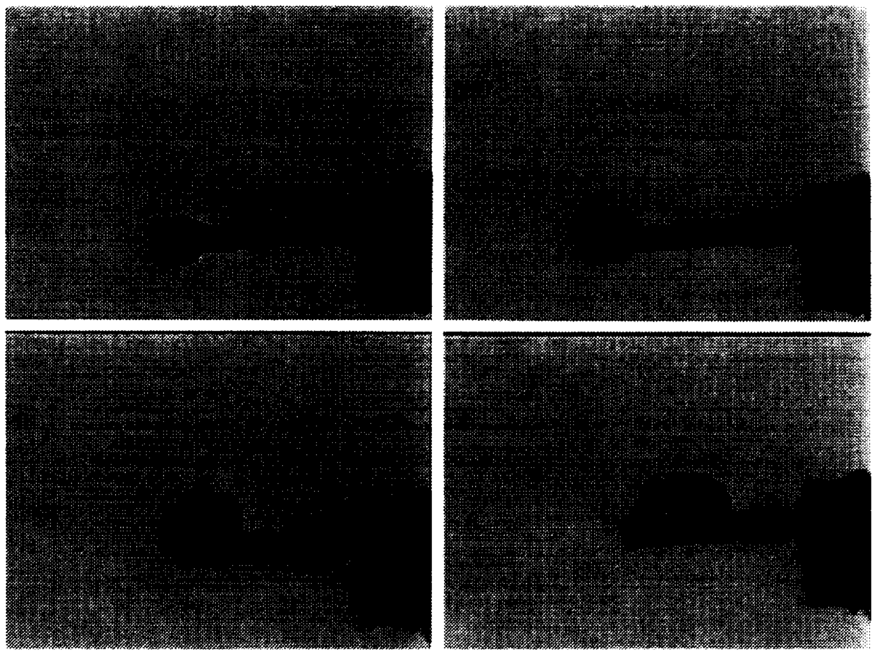


Deployment of 8 mm water droplet on T-injector with Teflon tip.



Another water droplet deployment. Note the extreme fluid deformation.

Though Freon-113, Silicone oil, and Ethyl Alcohol wet the Teflon tip only partially, that was not enough to prevent them wetting the Teflon tube and flowing down the outer walls of the tube (see Photo 12). A more nonwetting tip tube could alleviate the problem.



Water droplet on T-injector Teflon tip is pushed off of tip by oil, but the oil wets the Teflon tip, and the water droplet is not released.

One final note: as with the concentric injectors, the geometry of the tip appeared to play a role in deployment. The Teflon tip was flared slightly to provide more surface area to stabilize the droplet.

3.4 Comparison of Testing Methods

Three testing methods were used and each had advantages and disadvantages. Future researchers might be interested in knowing how which test method was the most effective. Neutral buoyancy testing was the least expensive and the injectors exhibited many of the problems encountered in more expensive low gravity testing. During neutral buoyancy testing, problems with experiment fluid wetting the concentric injector tip were observed. The primary limitation of neutral buoyancy testing is the requirement to use immiscible density matched fluids. The problems with Freon and alcohol did not surface until DC-9 testing.

The Zero Gravity facility testing was valuable but not a timely way of gathering data for this type of experiment. In the 5.2 sec drop tower tests, wetting was shown to be a problem as well as the unexpected effect of oil and water adhesion in microgravity. This facility provides the highest fidelity microgravity environment and would be most useful in final verification tests before building a shuttle based experiment of these injectors.

The DC-9 tests were perhaps the most valuable and effective tests for broad-based testing of many different parameters. DC-9 testing provided the freedom to test multiple fluid combinations at low gravity. Many low-gravity runs could be completed per day using a very inexpensive test rig.

4. POSSIBLE ENHANCEMENTS TO IMPROVE INJECTORS

Several aspects of the injectors could use improvement. The problems which prevented fluid deployment were wetting, bubble-formation, and instability of the droplets on the tip of the injector due to varying g-levels.

The problem of fluids wetting the injector tip could be solved by building a tip out of a nonwetting material or coating the tip with a nonwetting barrier coating. Research into this area could greatly improve the chance of a successful deployment.

The geometry of the tip of both the concentric and T-injectors greatly affects droplet formation and deployment. The tip design should allow minimal contact area with the fluid but yet allow enough surface area to prevent the droplet from rolling over the tip onto the side of the tip tube. A greater retraction of the inner tube tip from the outer tube tip could reduce or eliminate bubble formation on the concentric injector. Other properties such as tube tip surface roughness and chamfer angle might influence droplet deployment.

The fluctuating low-gravity levels on the DC-9 tests occasionally caused droplets to roll over the tip. In a space-shuttle environment with true microgravity levels, a highly smoothed tip ground to a razor's edge might be most effective.

Use of a very viscous fluid could dampen droplet oscillations and assist in the deployment process. High viscosity fluids have lower frequency of vibration and thus deployment might be achieved at lower velocities. Also, fluids with high surface tension might be more resistant to bubble formation since the force required to break the droplet surface could be higher than the force required to push the droplet off the injector tip. Liquids with viscosities greater than 10 centistokes were not tested.

One method to reduce droplet velocity might be to rapidly pull the injector back away from the droplet at the instant than it releasing from the tip. As mentioned earlier, many times a detached droplet reattached itself to the injector tip. Rapidly pulling the injector back from the droplet at the same time as the droplet is deformed might prevent droplets from reattaching to the injector tip.

5. CONCLUSIONS

Two new types of droplet injectors were built and tested. Testing of the droplet injectors consisted of neutral buoyancy tank tests, 5-sec drop tower tests at the NASA Lewis Zero Gravity Facility, and DC-9 tests. The concentric injector worked well in the neutral buoyancy tank but did not function well for deploying droplets in DC-9 tests. However, it made a fine apparatus for constructing bubbles in low-gravity.

The T-injector concept showed the most promise for future development. In both neutral buoyancy and DC-9 tests, water droplets were formed and deployed with some control and repeatability, although in low-gravity the deployment velocities were higher than desirable.

Further development work for the T-injector should include finding improved nonwetting barrier coatings or tip materials, refining the tip geometry to minimize attractive forces, and experimenting with different fluid combinations. Further DC-9 tests could improve and refine the technique and allow a higher degree of success for droplet/bubble deployments at low velocities.

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13. ABSTRACT *(Maximum 200 words)*

A free-floating droplet in microgravity is ideal for scientific observation since it is free of confounding factors such as wetting and nonsymmetrical heat transfer introduced by contact with surfaces. However, the technology to reliably deploy in microgravity has not yet been developed. In some recent fluid deployment experiments, droplets are either shaken off the dispenser or the dispenser is quickly retracted from the droplet. These solutions impart random residual motion to deployed droplet, which can be undesirable for certain investigations. In the present study, two new types of droplet injectors were built and tested. Testing of the droplet injectors consisted of neutral buoyancy tank tests, 5-sec drop tower tests at the NASA Lewis Zero Gravity Facility, and DC-9 tests. One type, the concentric injector, worked well in the neutral buoyancy tank did not do well in low-gravity. However, it appeared that it makes a fine apparatus for constructing bubbles in low-gravity conditions. The other type, the T-injector, showed the most promise for future development. In both neutral buoyancy and DC-9 tests, water droplets were formed and deployed with some control and repeatability, although in low-gravity the residual velocities were higher than desirable. Based on our observations, further refinements are suggested for future development work.

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