A ZERO "G" FLUID DROP INJECTOR FOR THE DROP DYNAMICS MODULE SPACELAB EXPERIMENT

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ABSTRACT

A fluid drop injector has been developed to form and release fluid drops into free drift within an experimental apparatus known as the Drop Dynamics Module which is to be flown on an earth orbiting Spacelab. To verify the design concept, a breadboard injector was flown on the NASA KC-135 zero "g" airplane after which more extensive laboratory 1 g tests were performed to improve the injector design and enable it to meet the module's functional requirements. The breadboard fluid drop injector will be modified and upgraded to flight hardware.

INTRODUCTION

A fluid drop injector has been designed, breadboarded, and tested for use in a science experiment facility known as the Drop Dynamics Module (DDM). The experiment is expected to be flown initially on Spacelab III. This zero "g" experiment facility will be used for various fluid drop experiments, the first of which is to study the dynamics of free fluid drops to verify existing theory, with potential application to droplet behavior in chemical processing, containerless processing of molten material and meteorology. The DDM will be installed in a double rack in a pressurized payload module, thus operating in a "shirtsleeve" environment.

The experimental apparatus comprises a chamber into which fluid drops are formed and released, an acoustical drop positioning and manipulating system, and a data collection system consisting of a movie camera which views the drops from three directions, see figure 1. The acoustical positioning and manipulation system produces drop centering forces through pressure gradients produced by standing waves generated by three acoustical drivers. The acoustics can also rotate or oscillate the drop through variation of the phase and amplitude of the acoustic waves. The DDM is being implemented as an

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automated experiment to minimize attention by the Payload Specialist, who will be required only to perform such tasks as replacing consumables, viz, changing fluid containers, film magazines and data tape cassettes, and chamber cleanup in experiments where fluid drops fragment and strike the chamber walls.

The fluid drop injector is required to produce drops of various fluids such as water and silicone oils of widely varying viscosities, surface tensions and densities, and of various sizes from about 0.6-2.5 cm (¼-1") in diameter. It must then release the drops in the center of a nearly cubical transparent chamber of about 15 cm cube (6") with essentially zero drift velocity and with minimal rotation, oscillation or production of secondary droplets and then must retract from the chamber.

FLUID INJECTOR REQUIREMENTS

Drop Volume,	0.25-10 cc (accurate to $\pm$0.03cc)
Fluid Viscosity Range	1-1000 centistoke(cs)
Fluid Pumping Rate	0.1-1.0 cc/sec
Maximum Drop Velocity (after release)	0.1 cm/sec
Maximum Secondary Droplet Volume	0.10% of drop volume

No contamination of drop with previous liquid used.
Form drops in 10^{-3} g field with no acoustical force field.
Release drop with minimum oscillation and rotation.

INITIAL FLUID INJECTOR DESIGN

1. To prevent cross contamination of fluids, all parts which contacted the fluid, such as pumps and injectors, would handle only a single fluid.

2. To provide accurate metering and minimize the net momentum of the drop, dual positive displacement pumps would be employed, operated by a single stepper motor. Each pump would discharge fluid through opposite facing injectors, thus providing equal flow rates with total volume proportional to the number of commanded motor steps.

3. Since the optimum positioning of injectors during drop growth and the optimum positioning and velocity of injectors during release of the drop were unknown, it was decided that programmable injector position and velocity servos would be employed for maximum design flexibility.

4. Since injector tip design was unknown, tips would be made replaceable. If possible, injector tips would utilize surface tension forces to stabilize the drops during drop growth.

5. Major unknowns in the design were parameters which controlled the production of secondary droplets.

BREADBOARD FLUID PUMP, INJECTORS & INJECTOR DRIVERS

Breadboard fluid drop producing devices were built in accordance with the initial design noted above. The pump, shown in figure 2, uses a computer controlled 200 step/revolution stepper motor to rotate a lead screw - a 5 cm (2") travel micrometer head - through suitable gearing to provide about 4.8 cm (1.9") of travel to a pump driver which pushes the plungers of two 50 cc gastight fluid filled syringes.

The driver is guided by three miniature ball bushings running on two guide rods. The gearing was selected to produce a fluid flow of very nearly 0.002 cc/motor step; thus, a 10 cc drop requires 5000 motor pulses which can be stepped in from 10 to 100 seconds. The motor is operated in the open loop mode.

Fluid discharged from the syringes flows through fluorocarbon elastomeric tubing to two oppositely facing injector tubes installed along a line passing through the center of the chamber. The injectors are, in turn, moved in and out of the chamber as desired by motor operated injector drivers, see figure 3, which are position and velocity servo controlled by computer operated controllers.

Each injector is installed in the hollow injector driver which is positioned axially by a rack machined into the driver. The driver is guided by three sets of rollers, one of which is spring loaded, and is driven by an aircraft quality dc motor through two stages of anti-backlash reduction gears. The drive gear for the rack also directly rotates both the injector position (single turn) potentiometer and, through suitable gearing, a small ironless armature dc motor which generates the voltage employed by the injector velocity servo. The injectors are guided by the rollers with sufficient accuracy to align their centerlines within a few thousandths of an inch when they meet at the chamber center. Although the functional requirements originally called for a minimum retraction velocity velocity of 100 cm/second in a distance of 0.5 cm - and the velocity of the breadboard injectors and drivers approached that velocity - investigations to be described later showed that the optimum retraction velocity was less than half that figure. The lower velocity was achieved by operating the motors at reduced voltage.

Replaceable injector tips are installed at the outlet end of each injector to suit the fluid characteristics and discharge rate. Replacement of syringes, injectors and flexible tubing is facilitated through the use of split, hinged clamps which secure the syringe barrels and plungers. Bubble free filling of fluid containers is essential and is expected to be a ground based operation.

FLUID DROP STABILITY ON A SINGLE INJECTOR TIP

Investigations indicated that there is a basic difference in the equilibrium positioning of fluid drops suspended on an injector tip in zero "g" if the contact angle between the drop and the tip is greater than 90° in the one case and less than 90° in the other. Figure 4 illustrates this point. If the fluid/tip contact angle is greater than 90°, as is the case for a water drop on a wax coated metal tip, the drop will not allow itself to be impaled on the injector tip but will move tangent to the end of the tip to maximize its surface energy. Figure 4 also shows that for liquid/tip contact angles of less than 90^{o}, e.g., a silicone oil drop on a PFOMA* coated metal tip, the drop cannot be made to stay tangent to the end of the tip (without the application of an external force) but will move back until the front of the drop is tangent to the end of the tip (i.e., the drop is impaled on the tip).

This difference in drop behavior (oil vs. water) can be eliminated by making both oil and water have a contact angle of 0^{o} which would make both behave like oil, with drops impaled on the tip. This idea was discarded as was the use of a single injector tip for three reasons:

(a) Deep immersion of the drop in the injector was suspected as being a contributor to the production of secondary droplets.

(b) Release of the drop with near zero net momentum in the absence of an acoustical centering force field appeared difficult.

(c) Achieving a 0^{o} contact angle required careful cleaning of the surfaces being contacted and high purity of the fluids. Maintenance of required tip cleanliness for multiple injections under flight experiment conditions would be difficult.

Accordingly the use of two PFOMA coated injectors was selected.

FLUID DROP STABILITY ON TWO INJECTOR TIPS

Figure 5 illustrates three possible injector tip shapes and indicates the net stability of a drop in the axial and radial directions resulting from the surface tension forces for fluid and tip coatings having contact angles 1) greater than 90^{o}; e.g., water/paraffin, glycerine/teflon, mercury/iron, etc., and 2) less than 90^{o}; e.g., petroleum or silicone oil/PFOMA, kerosene/glass, etc. It shows that for water on a "non-wetting" coating such as paraffin, drop stability can be achieved at the chamber center through the use of truncated cone shaped tips with small ends facing, whereas for silicone oil on a "non-wetting" coating such as PFOMA, stability can be achieved with truncated cones with bases facing each other. Therefore, other conditions

* poly (1,1-dihydropentadecaflourooctylmethacrylate)

permitting, the two cone shaped injector tips noted would be used.

IS PROGRAMMED INJECTOR MOTION NECESSARY?

The difference in direction of the axial force vectors for oil and water drops in contact with PFOMA* coated injector tips, figure 5, implies that oil drops and water drops require different injector positions during drop growth if programming of the motion is to be avoided. With water drops, the tips should be moved apart to a separation equal to or somewhat greater than the final drop diameter, and kept fixed during drop growth, whereas with oil the tips must be moved to a separation equal to the tip inside diameter or less and then held there until the drop is fully grown. Alternatively for both fluids, the tips can be moved together until they almost touch, then the fluid pumped until the two streams coalesce into a single drop, after which the injectors must be withdrawn at a varying rate so as to keep the drop periphery tangent to the two tips.

Determination of which motion technique was better awaited test results.

KC-135 ZERO "G" TEST

The breadboard pumps, injectors, and injector drivers, shown in figures 2 and 3 were tested qualitatively in three flights of the NASA KC-135 airplane at Clearwater, Texas in mid-1978, and demonstrated that water and silicone oil drops could be formed in zero "g" with and without the acoustical field, see figure 6. However, the flights did not demonstrate that the functional requirements could be met since the severe time limitations of zero "g"** and generally poor "g" conditions preceding and following "free float" necessitated injector tip geometries and fluid pumping rates not conducive to meeting these requirements, e.g., large diameter tips and high fluid pumping rates. The high speed motion pictures taken on the KC-135 flights did not provide adequate resolution to make accurate assessments of satellite (secondary) droplet sizes, but it was apparent that secondary drop volumes

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* There is no known coating capable of increasing the contact angle of silicone oil to $>90^{\circ}$.

** Zero "g" float durations were usually 5-10 seconds.

were much greater (20-30 times greater) than the 0.1% permitted by the functional requirements. Residual drop velocity was also difficult to determine and it was seldom possible to assess whether the airplane and/or experiment operators contributed to the drop velocity rather than the fluid injectors.

The KC-135 tests showed that the sources of drop disturbance and secondary droplets produced in drop release were the columns of fluid extending from either side of the drop in the wake of rapidly retracting injector tips. It was not known whether the sources of these columns were fluid pulled from the drop or fluid trailed from the rapidly accelerating injectors. In any case, after the columns attained some maximum length, they broke up into droplets whose diameter was approximately the column diameter.

In the formation of silicone oil drops on the KC-135, due to a programming error, the injector tips were moved apart before sufficient oil had been pumped and resulted in the formation of two drops instead of one. After several such runs, the controller was switched to manual operation and the injector tips were held close together during the entire fluid pumping period which resulted in the formation of single oil drops.

LABORATORY INJECTOR PARAMETRIC TESTS

Next laboratory tests were conducted to optimize injector parameters to (a) reduce the production of satellite droplets to less than 0.1% of the drop volume as called for in the functional requirements, and (b) minimize the disturbance to the drop caused by injector withdrawal. In addition, since only water and 100 cs silicone oil were injected on the KC-135 flights, oil of other viscosities, viz., 1000 cs and 10 cs were also tested. Injector tips and operating parameters were included which were identical to those used on the KC-135 flights for comparison. Parameters investigated included tip diameter, cone angle (for water tips), immersion depth into drop, and injector retraction velocity.

Since the KC-135 tests with 100 cs silicone oil had indicated that the total volume of secondary droplets was essentially independent of drop size, it was decided that the simplest test procedure would be to use a cup filled with oil (or water), simulating a drop of infinite radius and mount a single injector with its drive mechanism over the cup, immerse the injector tip to the desired depth in the fluid and withdraw the tip vertically upward at the desired speed while taking high speed motion pictures of the tip, surface disturbance and column or droplets of fluid.

Preliminary runs with various fluids noted indicated that the test procedure described above was adequate for determination of relative drop disturbance of all fluids. It was also adequate for testing relative secondary droplet volumes for water and 10 cs silicone oil, but it was marginal to poor for 100 cs silicone oil and totally unsatisfactory for 1000 cs silicone oil. This was due to the higher viscosity fluids stringing out to a length corresponding to full travel of the injector, then streaming down from the motionless injector under the influence of gravity until they had necked down to a smaller diameter column which finally broke up into satellite droplets, but not of the correct size nor volume.

As a consequence, it was decided to employ another technique for satellite droplet volume determination. This technique involved the operation of the injector in a horizontal or near horizontal attitude instead of vertical. Two arrangements were tried, the first having the tip pass through a clearance hole in the side of a cup. The hole was located close to the fluid top surface and sized so that fluid surface tension prevented leakage of fluid from the cup when the tip was inserted through the hole. The second arrangement used a cup filled to the top, into the surface of which the tip was inserted at an angle of about 15° above horizontal. Both of these techniques were satisfactory.

Another preliminary test was made to determine the source of the fluid which formed the column of fluid and, in turn, produced the secondary droplets. Injector tips were connected to a hypodermic syringe filled with the appropriate fluid and fluid was forced from the tip into the simulated drop (i.e., the cup) just before tip retraction. The tip was then retracted and the column and secondary droplets photographed (see figure 7). Similar tests were performed using tips with no orifices (rods were used instead of tubes). As results indicated only a minor difference in drop disturbances or production of satellite droplets with the two techniques, rods were used for subsequent tests and the conclusion reached was that the fluid forming the columns came from the drop.

LABORATORY TEST RESULT TRENDS

Test results generally confirmed expected trends, i.e.:

1) Smaller diameter injector tips produced smaller drop disturbances and smaller volumes of secondary droplets.
2) Smaller tip immersions produced smaller drop disturbances and decreased secondary droplet volumes.

Unexpected trends included the following:

3) Decreased injector withdrawal velocities (within the range tested) produced smaller secondary droplet volumes.

LABORATORY TEST RESULT - DISCUSSION

Results shown in figure 8 indicated that the secondary droplet volumes specified by the functional requirements could only be met through the use of very small size tips and/or minimal immersion of the tips into the drops. Minimal immersion of injectors meant that accurate programming of injector motion during the growth of oil drops was essential. The feasibility of these parameters depended upon other factors such as:

1) Could the small tip diameter produce sufficient stabilizing surface tension forces to retain the drop in a 10^{-3} g force field?
2) Was the injector driver servo resolution sufficient to permit small injector tip immersions?

3) Did the small tip allow acceptable fluid pumping rates with high viscosity fluids?

A calculation of the diameter of injector tip required to retain a 10 cc water drop in a 10^{-3} g field indicated that a minimum diameter of 0.04 cm (.016") is required. This is consistent with the 0.05 cm (.020") minimum O.D. of the sharp cone tested and found to meet the secondary droplet maximum volume allowed for a 0.25 cc drop at an immersion of 0.16 cm (1/16") Thus, a single tip size will be satisfactory for water drops of all sizes since controlling the position of each injector, hence the tip immersion to 0.04 cm (.015") is achievable. Finally, water can be pumped through an 0.04 cm (.016") diameter injector at the maximum required pumping rate of 1 cc/second.

A similar calculation for silicone oil drops indicated that a minimum tip outside diameter of 0.18 cm (.070") is required to support a 10 cc drop on them in a 10^{-3} g field; a 0.24 cm O.D. (.093") by 0.20 cm I.D. (.078") tip was selected. Test results (see figure 8) indicated that the minimum satellite volume can be met at a reasonable immersion only for drops larger than about 1 cc. Consequently, the use of a second, smaller injector tip size 0.11 cm O.D. (.042") x 0.07 cm I.D. (.03"), is required for oil drops from 0.25-1.0 cc volume. Since the maximum tip separation to insure coalescing of oil into one drop is .07 cm (.03") which is about the resolution limit of the position servo, the injector tips will be positioned to touch (i.e. zero gap). It is not possible to pump the higher viscosity oils through the small tip at rates much above the minimum, i.e., 0.1 cc/sec because of the very high pressure drop which swells the elastomeric tubing excessively and stalls the pump motor; however, a pumping time of 10 seconds for a 1 cc drop is quite acceptable. The larger size oil tip permits a pumping rate of 1 cc/sec with 1000 cs oil.

The use of the inverted cone shape for silicone oil injector tips to achieve axial drop stability was discarded since this shape results in increased satellite droplet volume and/or decreased fluid pumping rates because of smaller injector tip inside diameters.

Cylindrical (tubular) shaped tips were selected for the oil injector tips since these result in a minimum tip outlet diameter, produce positive drop stability in the radial direction and neutral drop stability in the axial direction.

CONCLUSION

A practical fluid drop injection system has been developed for the Drop Dynamics Module, capable of forming drops of a range of commandable sizes from liquids having a wide range of physical characteristics. This system employs:

- A volume and rate commandable stepper motor operated dual outlet positive displacement pump.
- Two oppositely discharging programmable servoed injectors which move from outside the test chamber to its center as programmed.
- Surface tension forces to provide drop stability during drop growth and release.
- An initial tip separation of less than the tip radius.
- An injector retraction motion which keeps the growing drop periphery tangent to the injector tip outlets.
- One size injector tip for water drops of all sizes (¼ - 10 cc).
- Two sizes of injector tips for oil drops: one for drops from ¼ - 1 cc and the second for drops from 1¼ - 10 cc volume.
- Programmed injector tip motions together with tip sizes which minimize the production of satellite droplets and disturbance to the drop during its release into free drift.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100.

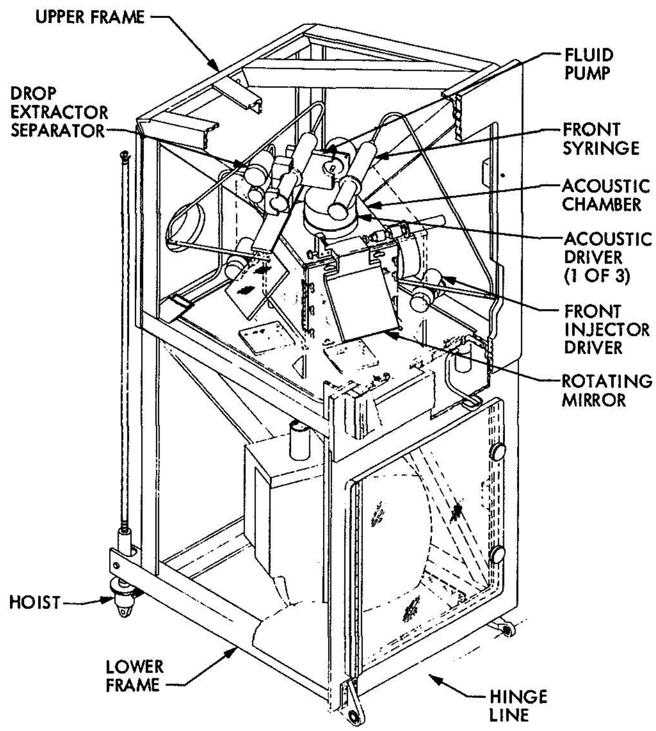

Fig. 1. Drop Dynamics Module Mechanical Module

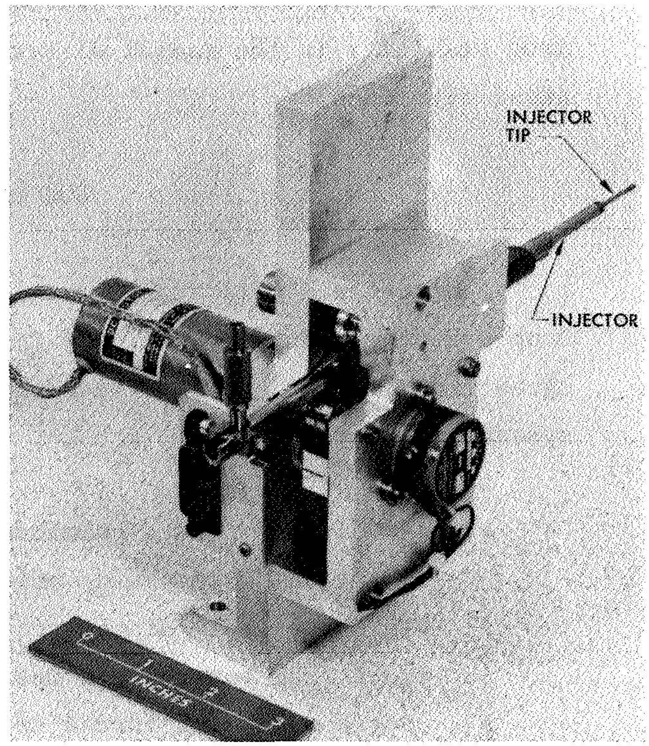

Fig. 3. DDM Fluid Injector and Driver

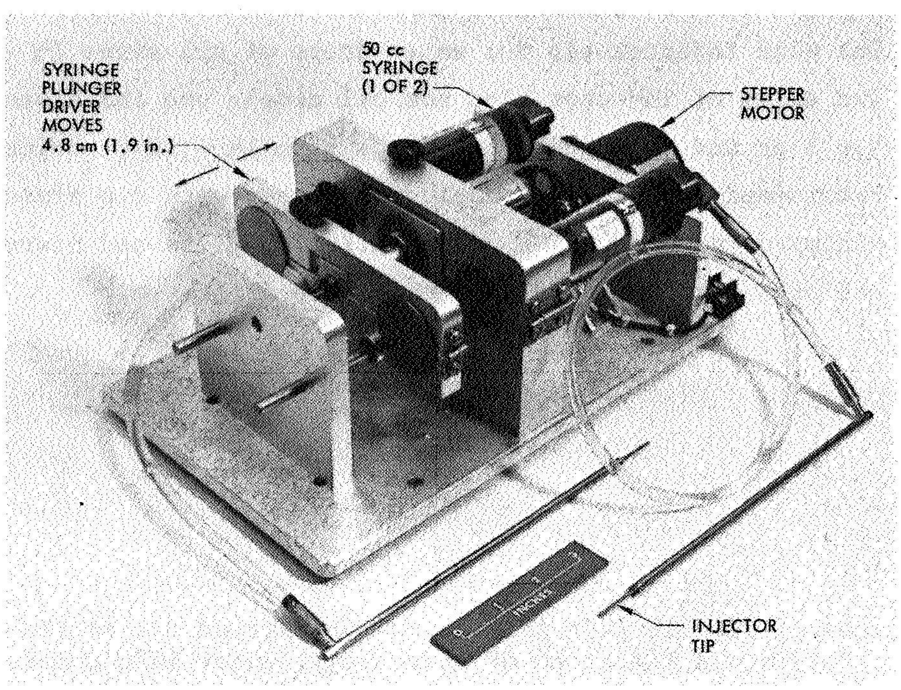

Fig. 2. DDM Fluid Pump

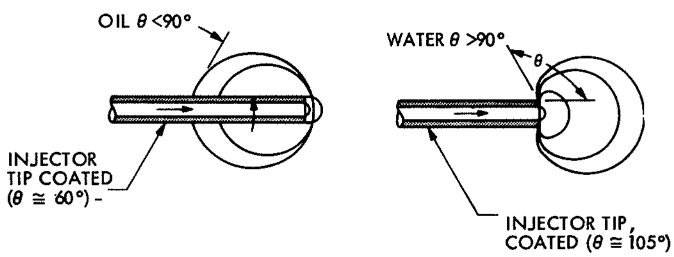

Fig. 4. Basic Drop Formation on Single Injector Tip

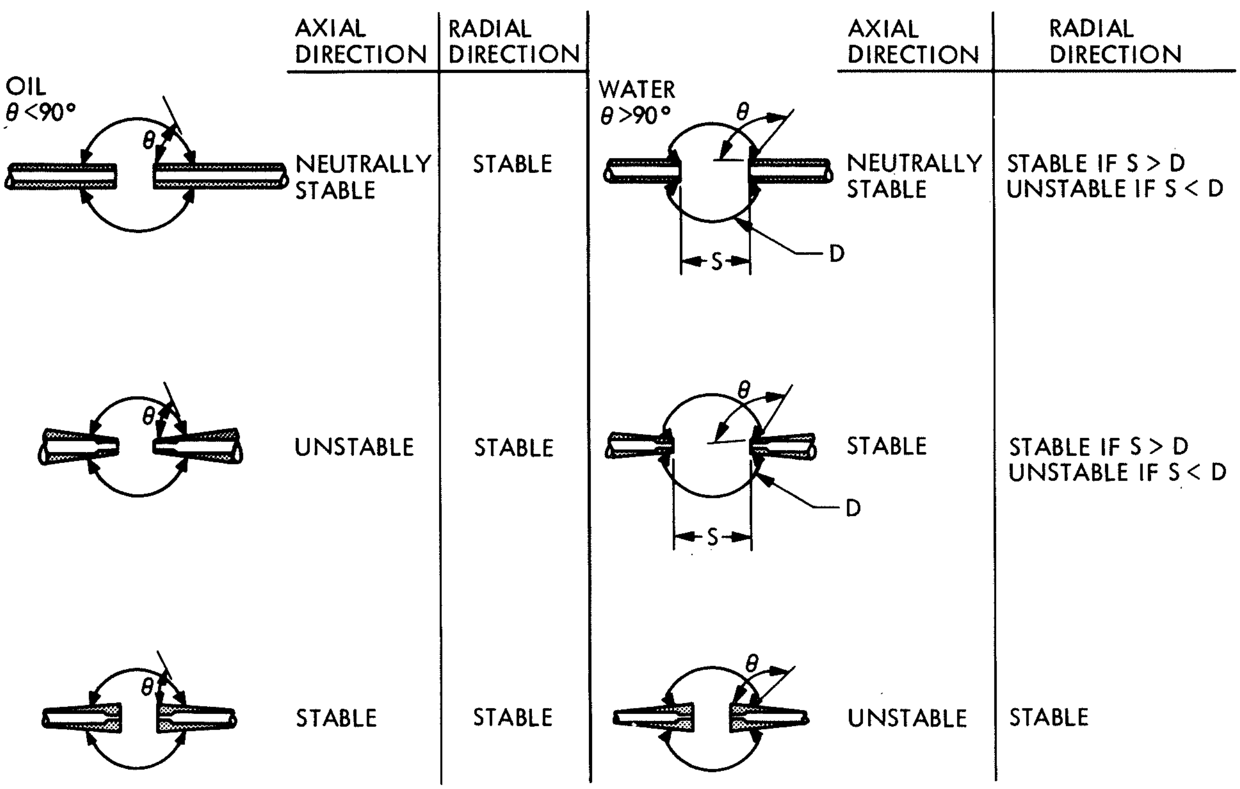

Fig. 5. Stability of Fluid Drops on Two Injector Tips vs Tip Geometry

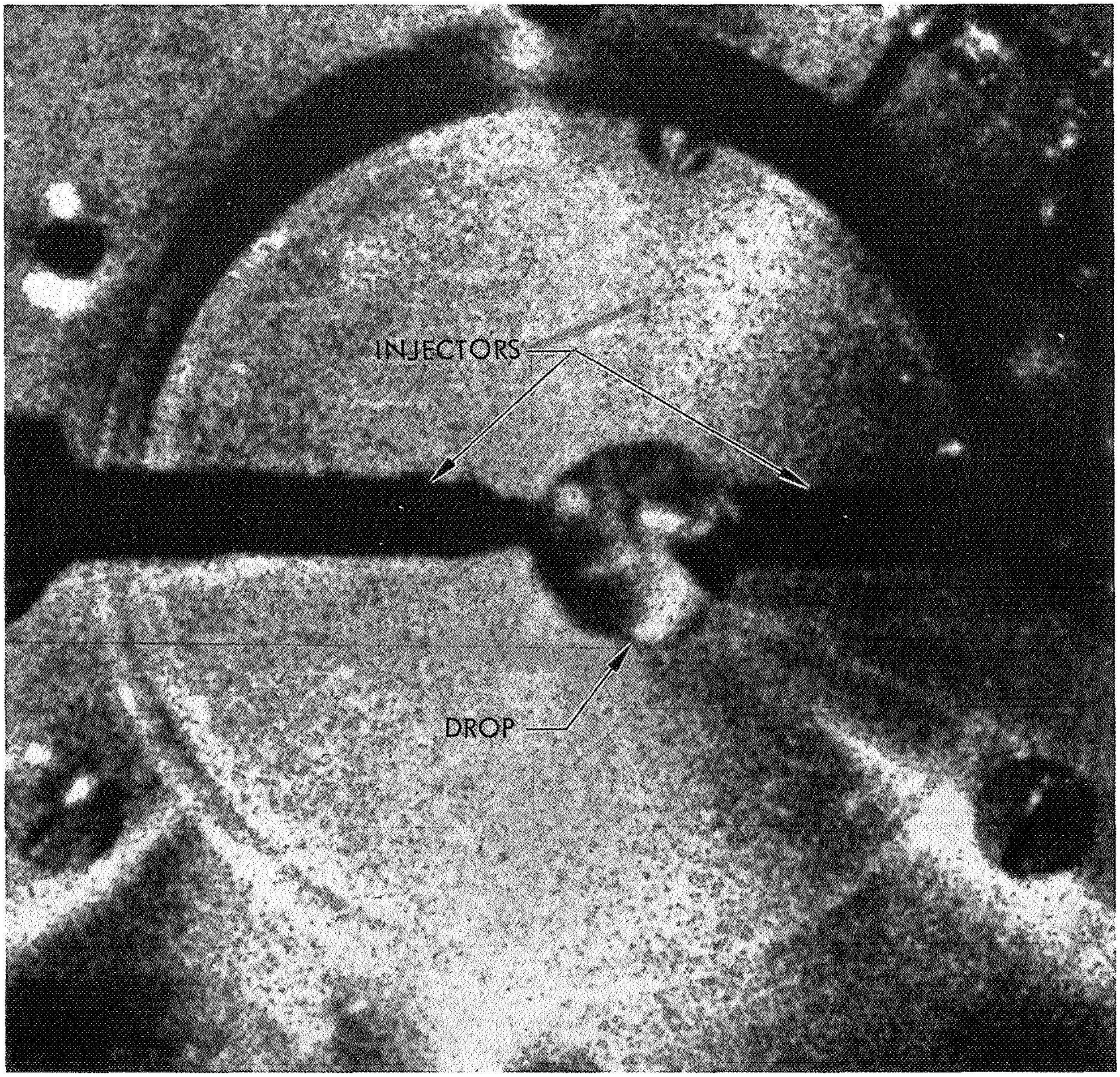

Fig. 6. KC135 Flight - Water Drop Forming in Zero "G"

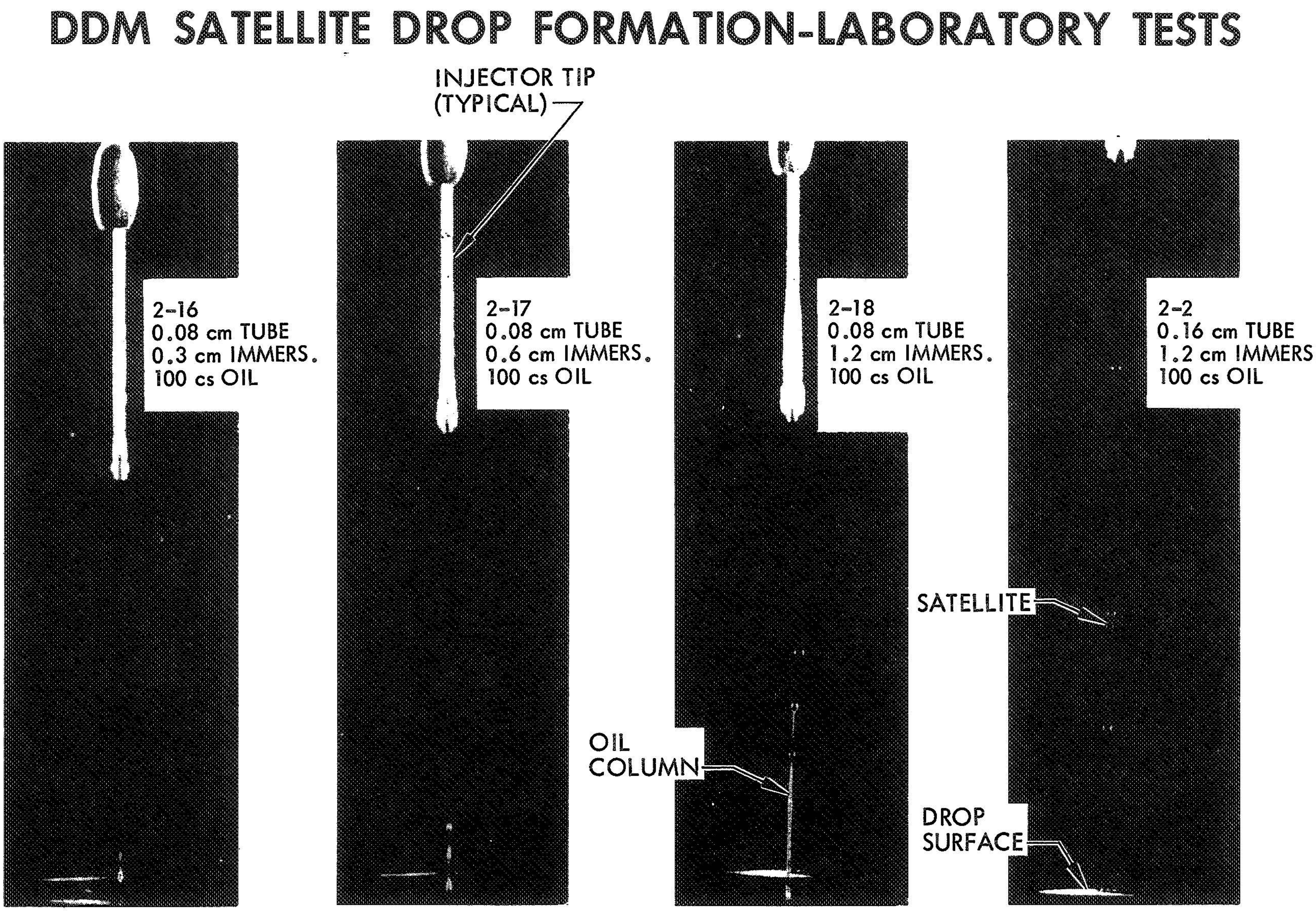

Fig. 7. DDM Satellite Drop Formation - Laboratory Tests

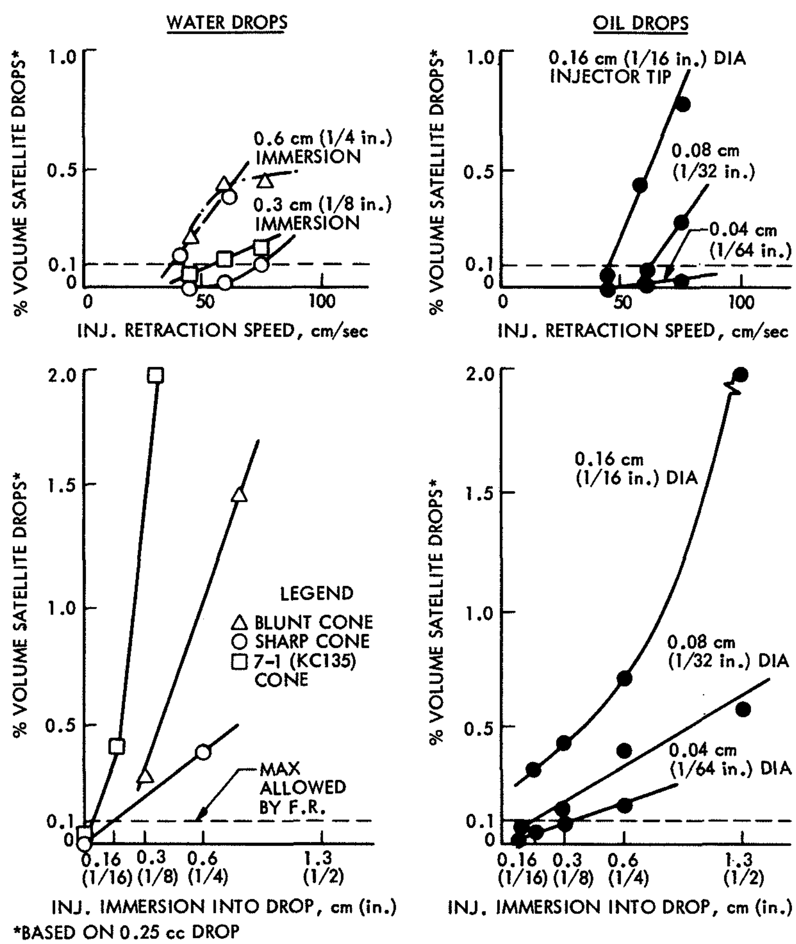

Fig. 8. Laboratory Test Results - Injector Parameters - Effect on Satellite Drop Volume