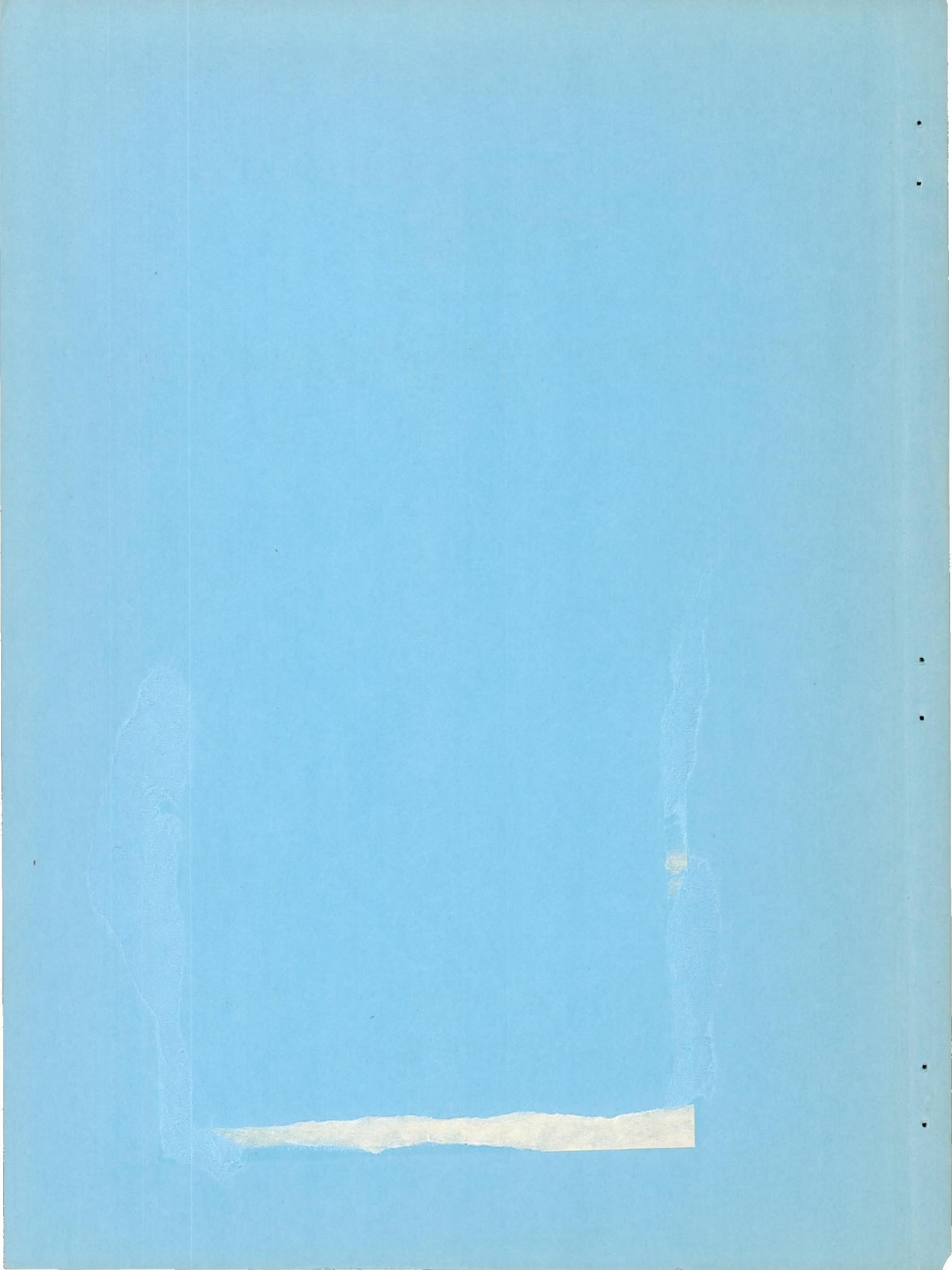RM E50K01a

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RESEARCH MEMORANDUM

FLIGHT CAMERA FOR PHOTOGRAPHING CLOUD DROPLETS

IN NATURAL SUSPENSION IN THE ATMOSPHERE

By Stuart McCullough and Porter J. Perkins

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

A camera designed for use in flight has been developed by the NACA Lewis laboratory to photograph cloud droplets in their natural suspension in the atmosphere. A magnification of 32 times is employed to distinguish for measurement purposes all sizes of droplets greater than 5 microns in diameter. Photographs can be taken at flight speeds up to 150 miles per hour at 5-second intervals. A field area of 0.025 square inch is photographed on 7-inch-width roll film accommodating 40 exposures on an 18-foot length. Flight tests conducted in cumulus clouds have shown that approximate droplet-size distribution studies can be obtained and that studies of the microstructure and physics of clouds can be made with the camera.

INTRODUCTION

In the study of the physics of clouds and the meteorological factors that are conducive to the icing of aircraft, it is necessary to measure the sizes of the droplets within the clouds. Measuring methods that involve catching the droplets while traveling at flight speeds are subject to errors resulting from impact which cannot easily be evaluated. The true sizes of the droplets can best be obtained while the droplets are in their natural suspension in the atmosphere. One method by which this may be accomplished in flight is to take high-speed photographs of the cloud using a suitable magnification system to distinguish the individual droplets. The sizes of the droplets can then be measured directly from the film with an accuracy that may be easily evaluated in the laboratory. This technique has been investigated by the National Research Council of Canada (reference 1).

Reported herein is a description of a camera and associated equipment for photographing cloud droplets in flight. The camera was constructed and flight tested at the NACA Lewis laboratory.

DESIGN CONSIDERATIONS

Three optical systems considered for the camera were based on
(1) the use of reflected light from the cloud droplets, (2) dark field
illumination whereby the droplets are made visible by refraction, and
(3) light field illumination in which the droplets appear as shadows.
It is extremely difficult to illuminate the droplets in such a manner
that the reflected or refracted light will define the perimeter of the
droplets against a dark background. The shadowgraph method was selected
for this camera because of the easier illumination problem and because
of the better contrast obtained with the shadow of the droplet focused
on the film. It appears that the diffraction effects encountered near
the limit of resolution of an optical system do not diminish the con-
trast at the edge of the image as much with a dark image as with a
bright one.

A schematic diagram of an elementary shadowgraph optical system
and camera is shown in figure 1. The first consideration in the design
of such a system is the resolving power of the objective lens. From
a standpoint of physical optics it has been shown that

$$X = \lambda \frac{L}{D}$$

where

X   the minimum distance resolved

L   object distance

D   lens diameter

λ wave length of light

In view of the fact that available panchromatic roll film is sensitive
to about 7000 angstroms and it is desired to resolve 5-micron particles,
the use of this formula gives an L/D value of 7. This value is the
theoretical resolution of two bright points by a perfect lens. Any
lens aberrations will require that this value be depressed. It has
been experimentally determined that, in order to accurately correlate
image diameters with object diameters in a shadowgraph system, the
value of L/D must be reduced at least 15 percent, giving a maximum
value of 6. Images of small-size particles that are near the limit of
resolution of an optical system will generally have less depth of focus
and apparent magnification than an image of larger particles. This op-
tical characteristic is the result of diffraction effects.

The depth of focus of a lens can be approximately expressed as

$$\Delta L = O_c \; \frac{2L}{D}$$

where ΔL is the depth of focus and O_c is the diameter of the virtual image of the circle of confusion as referred to the object plane. The magnification is approximately inversely proportional to the object distance and, therefore, a large depth of focus would cause excessive variation in magnification. It is desired, however, to photograph a maximum volume of cloud, which would indicate the desirability of a large depth of focus and a still larger object distance. A clearance of about 4 inches between the objective lens and the object plane was considered essential in order to be reasonably certain that the droplets were not being disturbed by the camera body before reaching the field of view. Calculations based on these values indicated that variation in magnification would not be a problem but that the volume to be photographed would be relatively small.

The grain size of roll film of moderate speed is of the order of 25 microns. Experience indicated that a minimum magnification of 25 times was required to obtain an image of a 5-micron object with sufficient contrast to be accurately measured on the film. A camera 9 feet long would be required to obtain this magnification with a simple single-lens system. In order to reduce this length and simplify other design considerations, a two-lens system was adopted as shown in figure 2. In this sytem an enlarged intermediate image of the object is formed between the two lenses near the second or projection lens.

The large relative velocity of camera and droplets at flight speeds requires that a very short exposure or some method of compensating for this velocity or a combination of both be used for stopping the image of the droplets on the film. At the time the camera was designed, the fastest suitable spark that was available was approximately 0.1 microsecond (reference 2). The minimum airspeed at which the camera would be required to operate in flight was taken as 150 miles per hour, at which speed a droplet would move 6 microns in 0.1 microsecond. Although limited droplet-size measurements could be made from the resultant photographic images taken in this exposure period, it was decided to compensate this motion by the use of a rotating mirror. The rotational speed of the mirror was adjusted to compensate for a linear velocity of 150 miles per hour.

DESCRIPTION OF INSTRUMENT

Construction. - A 3-inch F4.5 enlarging Ektar lens and a 50-mm F1.9
Ektar lens were selected for this application, because of their suit-
able correction. The permissible angular aperture of the system was
found to be limited by the available camera, which uses 7-inch-width
roll film, rather than by the correction of the objective lens.

An image of the light source was formed by the condensing lenses
mounted in the light-source housing at a point between the object plane
and the objective lens. This arrangement was required because the diam-
eter of the field of view was less than the diameter of the objective
lens and the apertures of both the objective and the projection lenses
require illumination from all points in the field of view. This light-
beam configuration produced the best resolution and also provided a
small image of the light source behind the projection lens where the
small rotating mirror was located. A 400-cycle induction motor was used
to drive the rotating mirror at speeds near 10,000 rpm. Motor speed,
being a function of inverter frequency, did not need to be measured or
otherwise regulated. The inverter governor was set to correspond to
the mean cruising speed (150 mph) of the aircraft in which the camera
was installed.

The flash from the spark light source must be initiated when the
shutter of the camera is open and within a few microseconds of the time
when the rotating mirror is in the proper angular position. The unit
that synchronizes the light source with the rotating mirror (fig. 3)
employs a small cup on the end of the induction motor shaft. The cup
has a small hole in one side. The image of a lamp located at one end
of the unit is focused on this hole so that one pulse of light is ad-
mitted to a photocell each revolution. The electrical pulse thus pro-
duced in the photocell has a fast rise time and is of several micro-
seconds duration. This synchronizing pulse signal is first passed
through a cathode follower in the synchronizing unit to lower the im-
pedance for transmission to the pulsing unit (fig. 4). The signal is
then passed through a pulse amplifier of conventional design (fig. 5)
equipped with an interlocking circuit connected to the camera shutter.
Thus, when the shutter has opened, the plate circuit of the cathode
follower output tube is completed through a condenser and the next
pulse is applied to the grid of the 5C22 hydrogen thyratron tube. The
tube becomes conducting, and the condenser connected to ground is dis-
charged through the series circuit consisting of tube, inductance, and
condenser. Energy is thus transferred to the inductance from the con-
denser and, as this oscillation continues, is returned to the condenser
but of opposite polarity. The tube then deionizes so that the oscilla-
tion is terminated after its first half cycle. The condensers are

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then in series and a voltage pulse of magnitude nearly double the sup-
ply voltage is applied to the light source. The considerations concern-
ing the use of this type of pulsed light source are discussed in detail
in reference 2.

The light source consisted of two 0.007 × 0.1 inch magnesium rib-
bon electrodes spaced 1/4 inch apart and sandwiched between quartz in-
sulating plates. The light emitted from the thin side of the electrodes
is used, thus obtaining a near point light source. The light-source
holder (fig. 4) was made removable from inside the airplane to provide
for possible service in flight. This convenience has not proved es-
sential, but the light source's being removable from the housing with
cable attached has greatly simplified assembly, disassembly, service,
and electrical insulation.

The mechanism of an aerial camera (K-21) was incorporated with
some modifications. This camera is an electrically operated automatic
unit using 7-inch width roll film in 18-foot lengths. It is equipped
with a focal-plane shutter and a pair of hinged doors that also oper-
ate as a shutter and normally close while the focal-plane shutter is
being rewound. The original camera lens, lens mount, and focal-plane
shutter were removed and a switch was added that makes contact when
the shutter doors are open. This interlock switch was previously des-
cribed in the synchronizing circuit.

Mounting on airplane. - Problems associated with mounting the
camera on the airplane dictated its external configuration (fig. 6).
The film-transport mechanism and synchronizing unit were mounted in-
side the airplane. In order to place the object plane as far from
the skin of the airplane as possible, the light-source housing was
supported about 18 inches from the airplane by five stainless-steel
tubular struts.

One end of each strut was attached to the light-source housing
with a stud that was silver-soldered to the shell. The other end of
each strut was attached with flanged unions to a mounting plate on the
camera body located inside the airplane. The unions permit disassembly
of the light-source housing from the camera body to facilitate mount-
ing the entire unit on the airplane. Upon reassembly the optical sys-
tem is alined without requiring any adjustments. Figure 7 is a photo-
graph of the camera mounted on a twin-engine aircraft.

Operation. - The thyratron tube requires a 5-minute minimum warm-
up period before pulsing. After the unit is loaded with film and suf-
ficiently warm, operation is controlled by the standby switch, which

turns on the prism motor and high voltage, and the operating pushbutton.
A photograph is automatically taken each time the pushbutton is de-
pressed. No synchronizing adjustments are required within ±40 miles
per hour of the intended airspeed. This allowable variation is of con-
siderable advantage when maneuvering the airplane to study different
portions of a cloud.

TYPICAL DATA

Measurements of the properties of the optical system indicate that
the area of the field recorded on the film is 0.025 square inch, al-
though the optical system is useful at full resolution at much more
than this area. Depth of sharp focus for 5-micron particles is 0.012
inch, and for sharp focus of 10-micron particles and larger it is 0.020
inch. Magnification is 31.6 times. With an object distance of approxi-
mately 4 inches, errors in magnification are negligible, being a total
variation of less than 1/2 percent for sharp focus and 2 percent for
anything that is defined on the film. If the exposed lenses become
wet or frosted when the cloud is heavy, some light will be dispersed
and the contrast of the droplet shadows will be less. No data have
been lost as a result of this effect.

Portions from several photographs taken during flight through
cumulus clouds are shown in figure 8. These areas have been enlarged
about 3 times from the original negatives to facilitate diameter meas-
urements of the droplet images. The number of droplets photographed
for each exposure varied from about 12 droplets to no droplets within
the field of view. It was extremely difficult from visual observations
to determine the more dense parts of the clouds where a greater number
of droplets for a given area can be expected. During one cloud survey,
a total of 24 exposures provided only 109 droplet images suitable for
measurement. These data are shown in figure 9, where the cumulative
frequency distribution of the droplet sizes is plotted on a probability
scale. These data indicate that studies of droplet-size distributions
are possible with the camera provided a large number of photographs
can be obtained.

The value of this camera is not necessarily confined to the meas-
urement and analysis of droplet sizes. Studies of the microstructure
of clouds can be conducted with regard to cloud development including
droplet nucleation, growth, coagulation, and evaporation. Phase changes
can also be detected. Ice crystals and snow flakes can easily be dis-
tinguished from each other and from liquid droplets. Various types of
ice crystals photographed while in natural suspension are shown in

figure 10. The irregular shapes of the images identify the ice crystals. These pictures were obtained in a laboratory cloud chamber where crystallization of liquid droplets can be controlled.

CONCLUDING REMARKS

A camera designed for use in flight has been developed by the NACA Lewis laboratory to photograph cloud droplets in their natural suspension in the atmosphere. All sizes of droplets above 5-micron diameter can be measured from the droplet images on the film. A shadowgraph technique is employed with an optical system providing a magnification of 32 times. A field area of 0.025 square inch is photographed on 7-inch-width roll film accommodating 40 exposures on an 18-foot length. Photographs can be taken at flight speeds up to 150 miles per hour at 5-second intervals.

Experiments conducted with the camera in flight and in the laboratory have provided the following results:

1. Cloud droplet-size distribution studies are possible provided a large number of photographs are used.

2. The photographs provide a means of studying the microstructure of clouds and the physical phenomena involved in cloud development and dissipation.

3. Images of ice crystals and snow flakes can be distinguished from each other and from liquid droplets.

Lewis Flight Propulsion Laboratory,
    National Advisory Committee for Aeronautics,
        Cleveland, Ohio.

REFERENCES

1. Elliott, H. W.: Cloud Droplet Camera. Rep. No. MI-701, Div. Mech. Eng., 6220 F-241, Nat. Res. Labs. (Ottawa), Dec. 26, 1947.

2. Young, Allen E., McCullough, Stuart, and Smith, Richard L.: Power Unit for High-Intensity Light Source. NACA RM E50K27.

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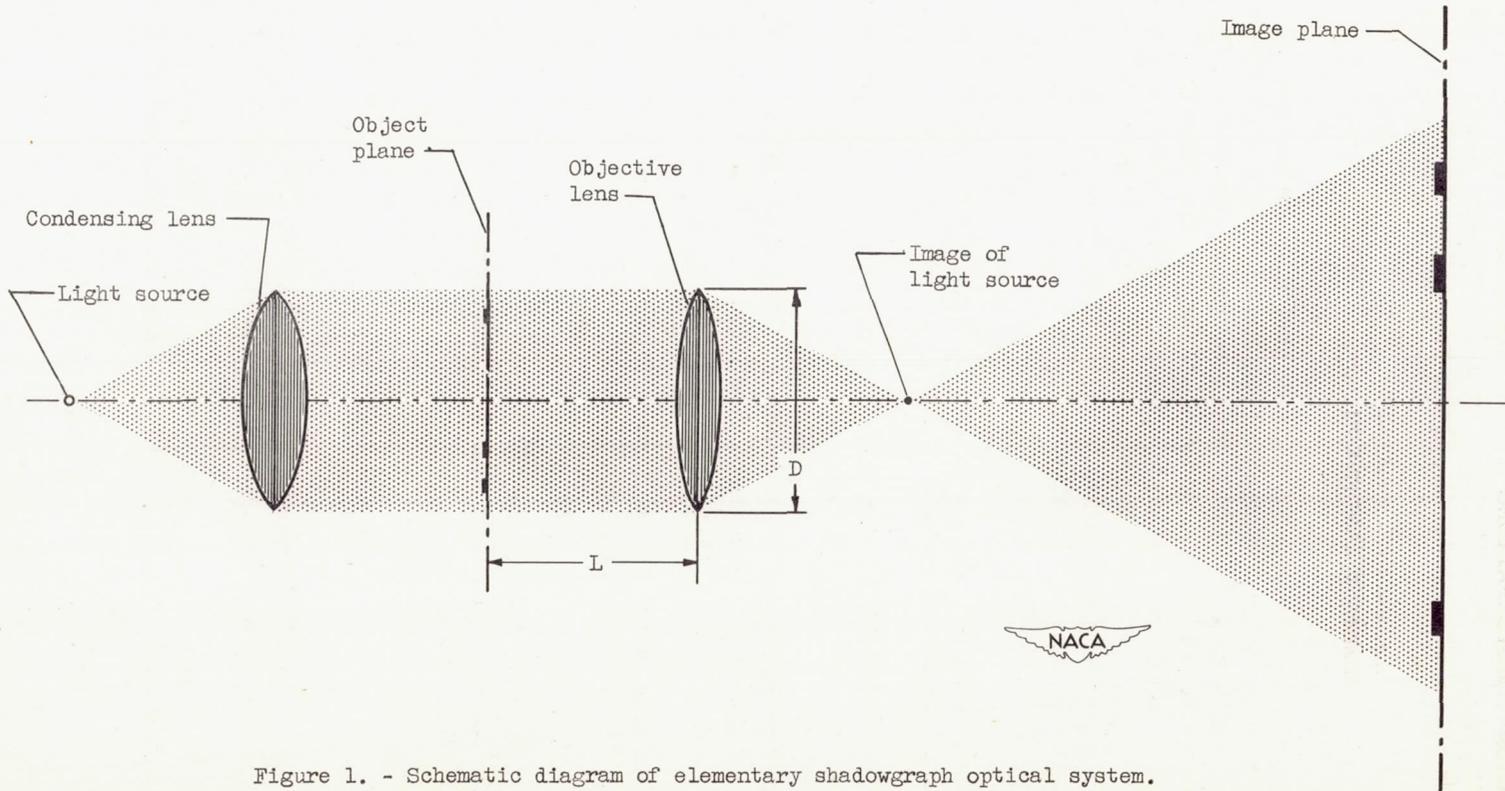
Figure 1. - Schematic diagram of elementary shadowgraph optical system.

Rotating mirror

Projection lens

Film

Intermediate
image plane

Airplane skin

Objective lens

First image of
light source

Object plane

Condensing lenses

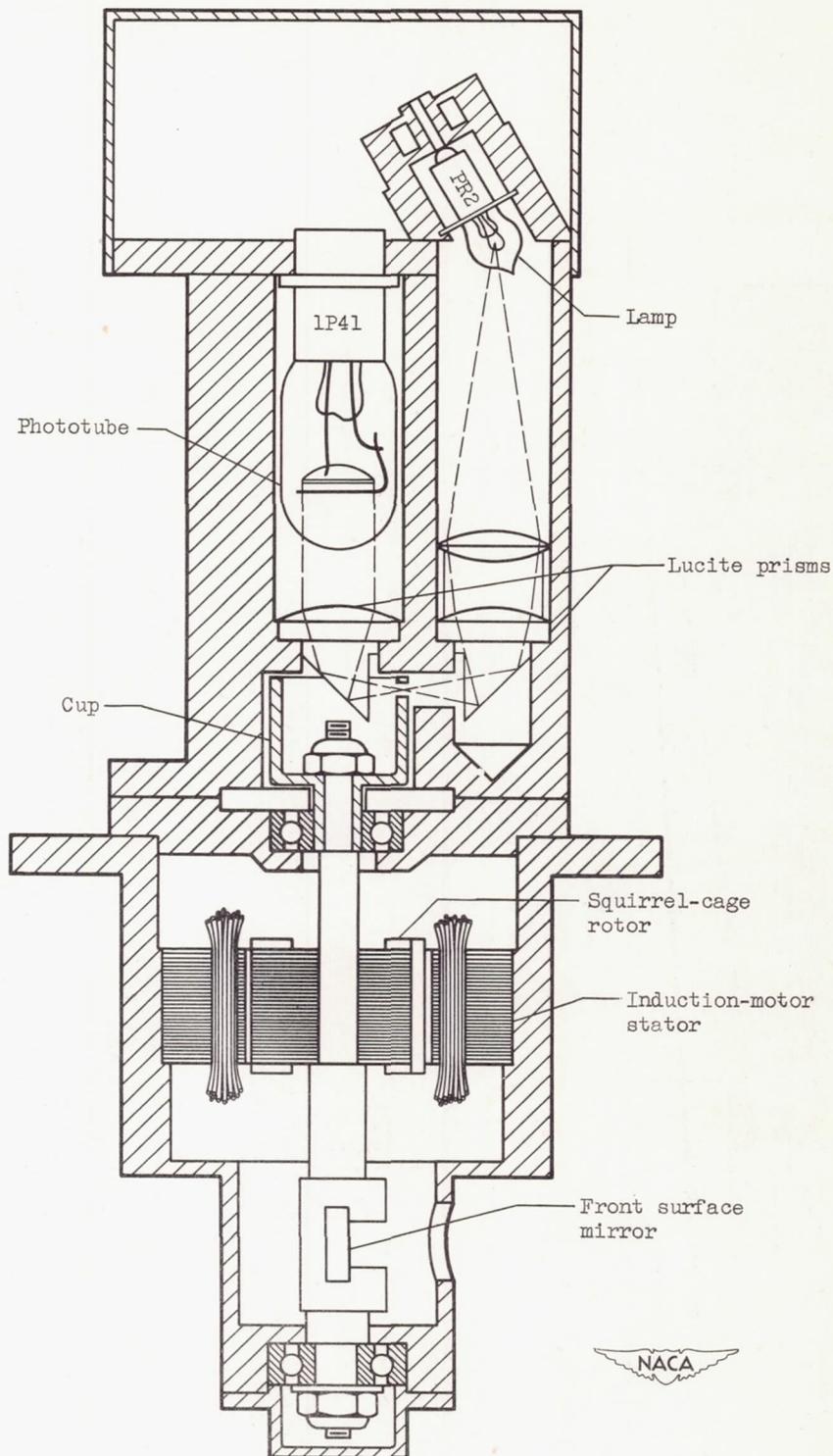Spark light source
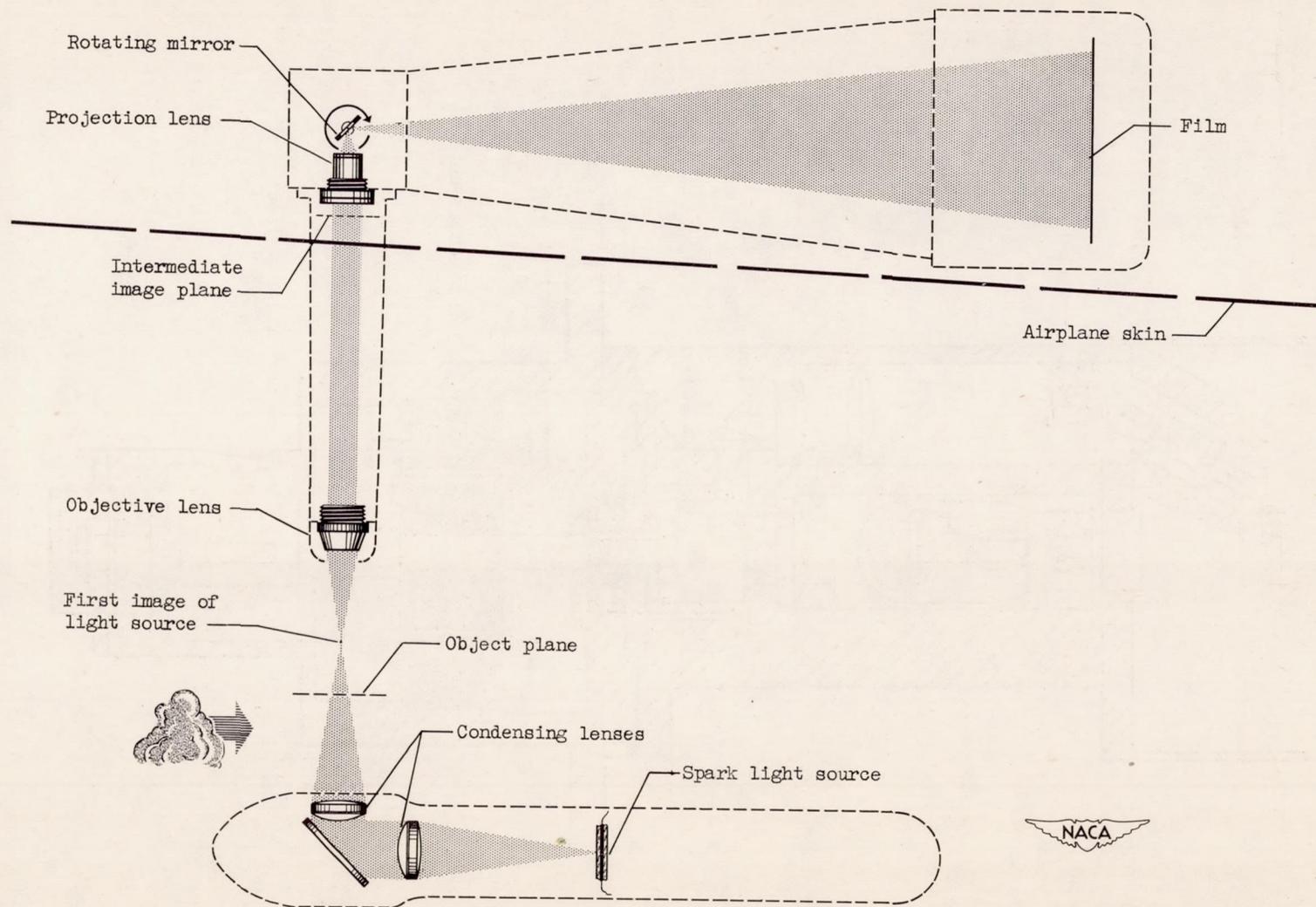
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Figure 2. - Droplet-camera optical system.

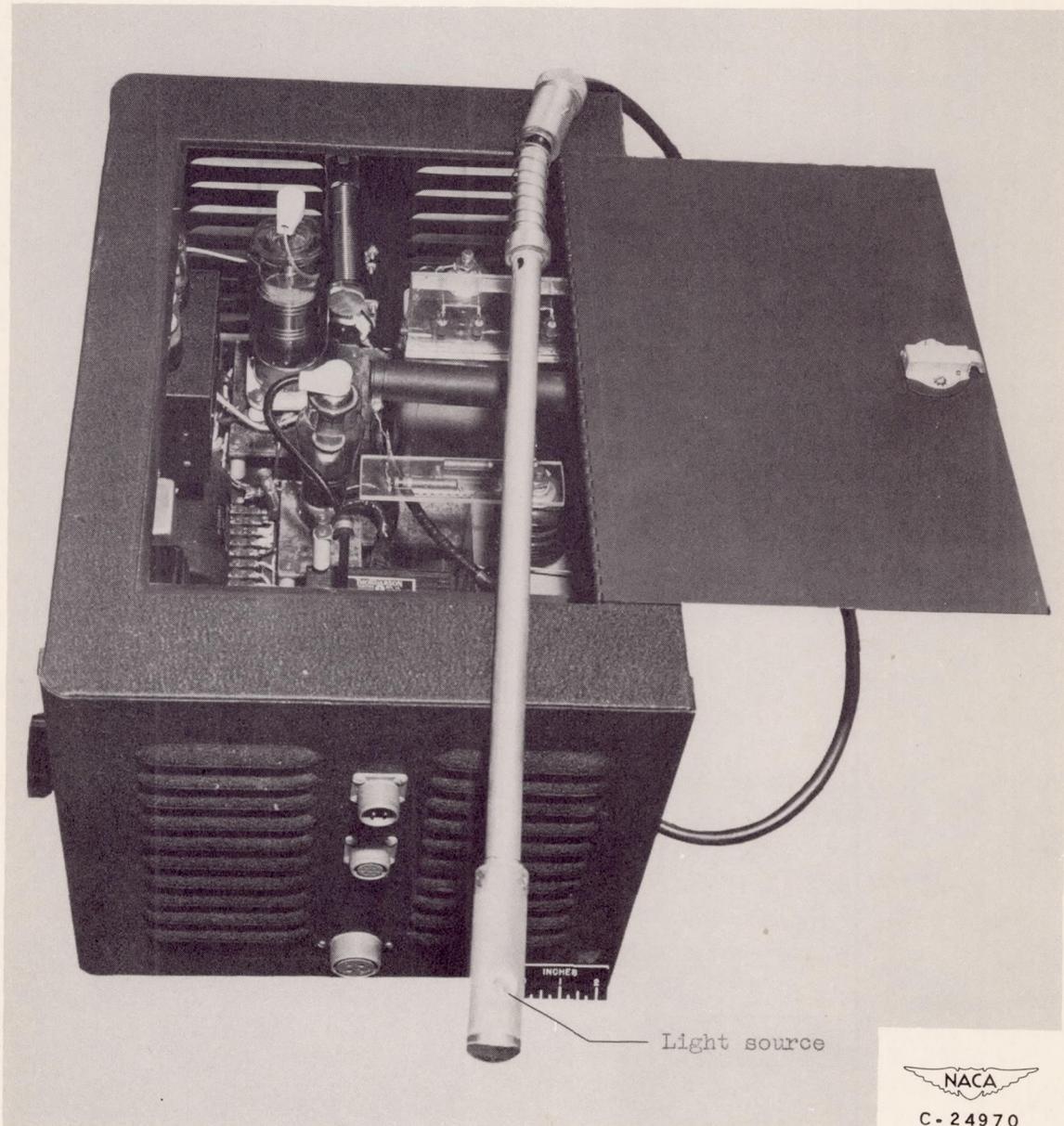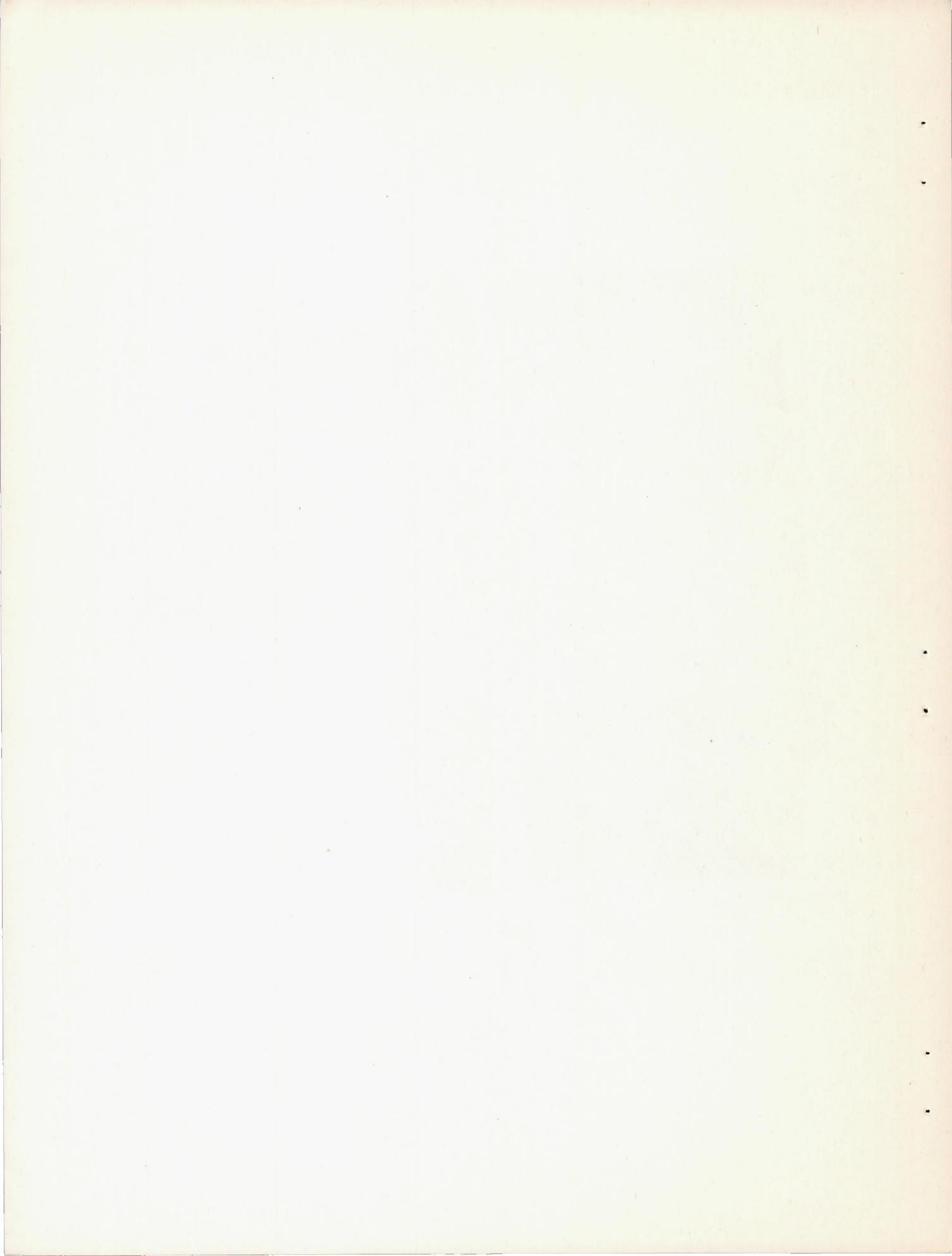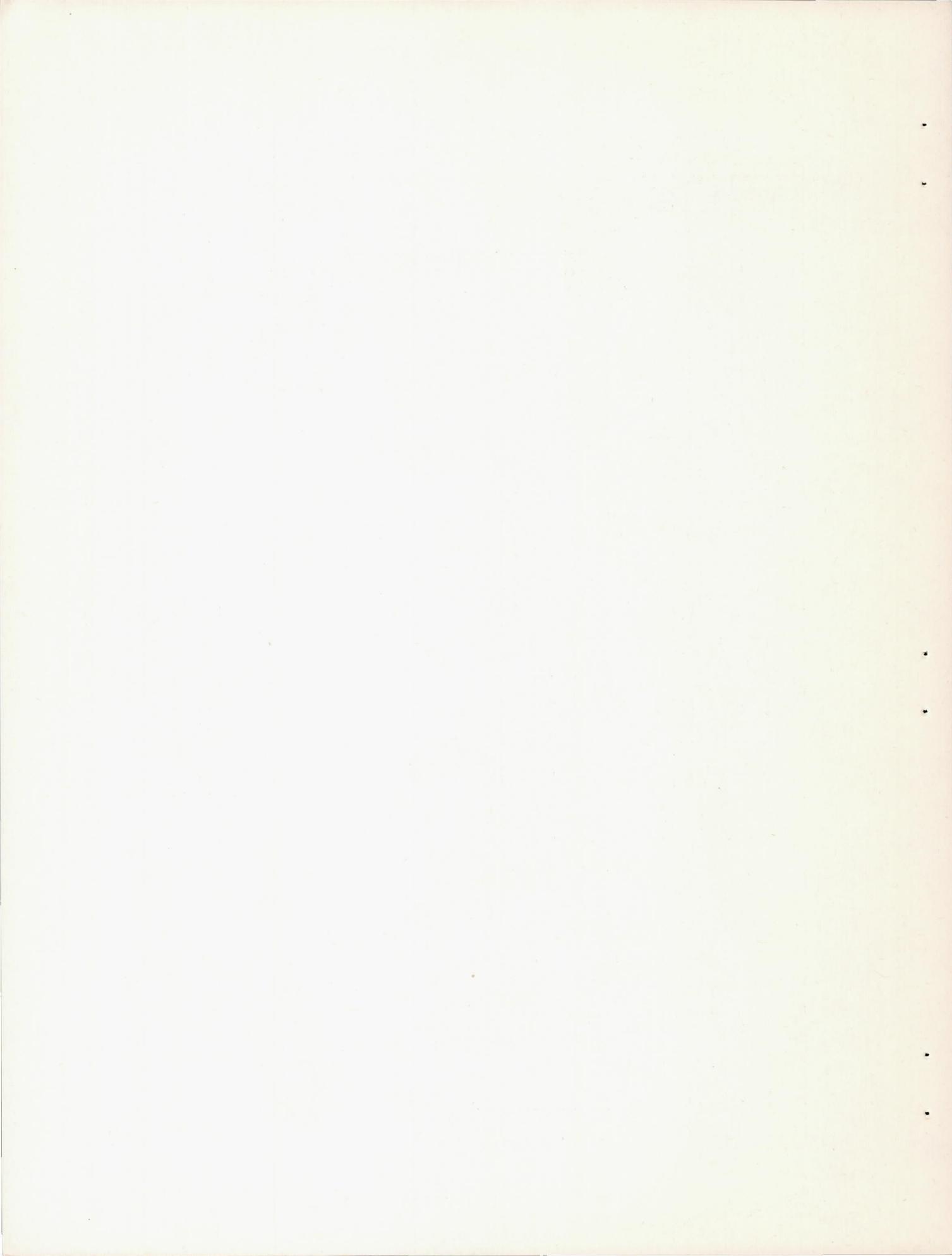Figure 3. - Mirror-drive and synchronizing unit of droplet camera.

Light source
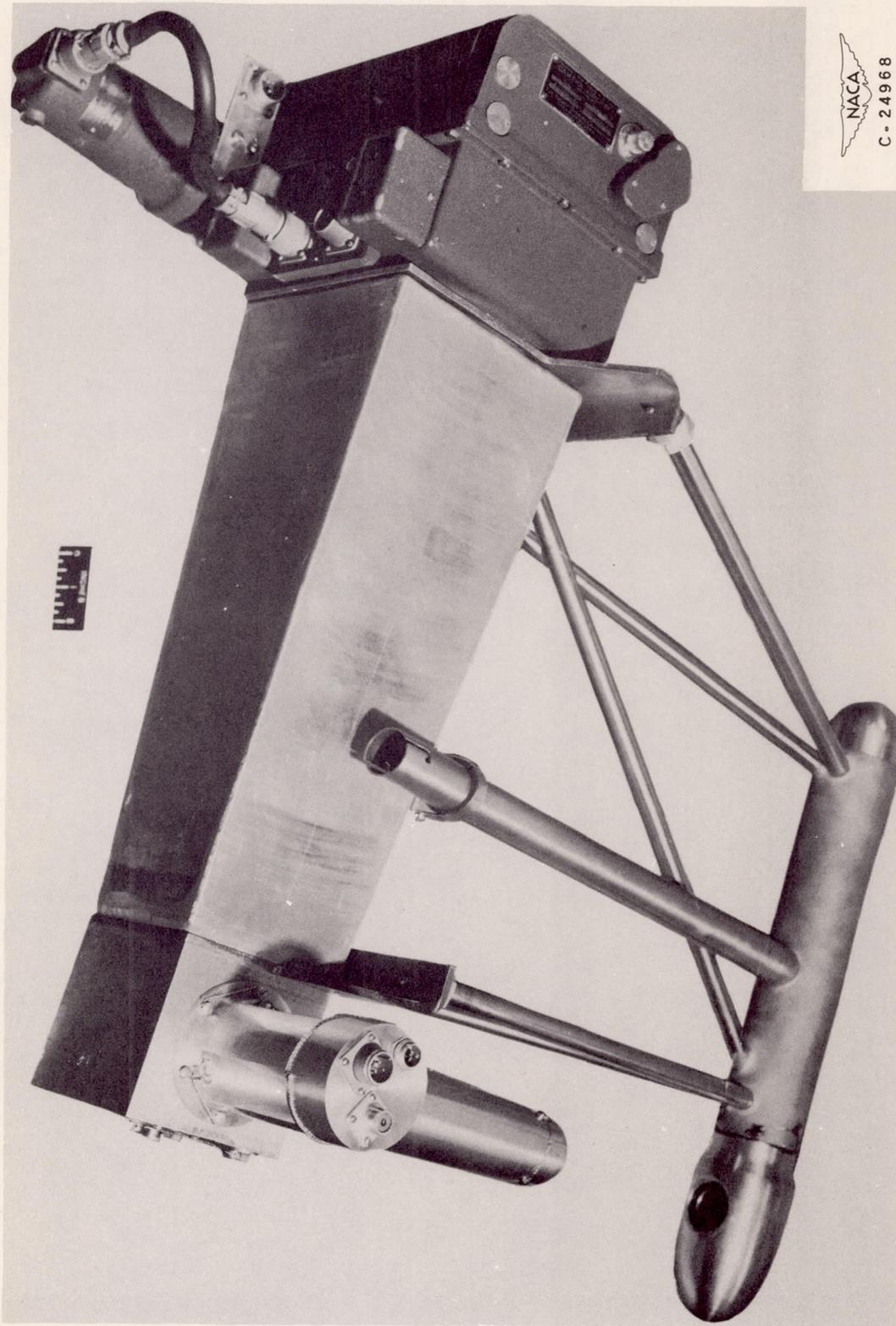
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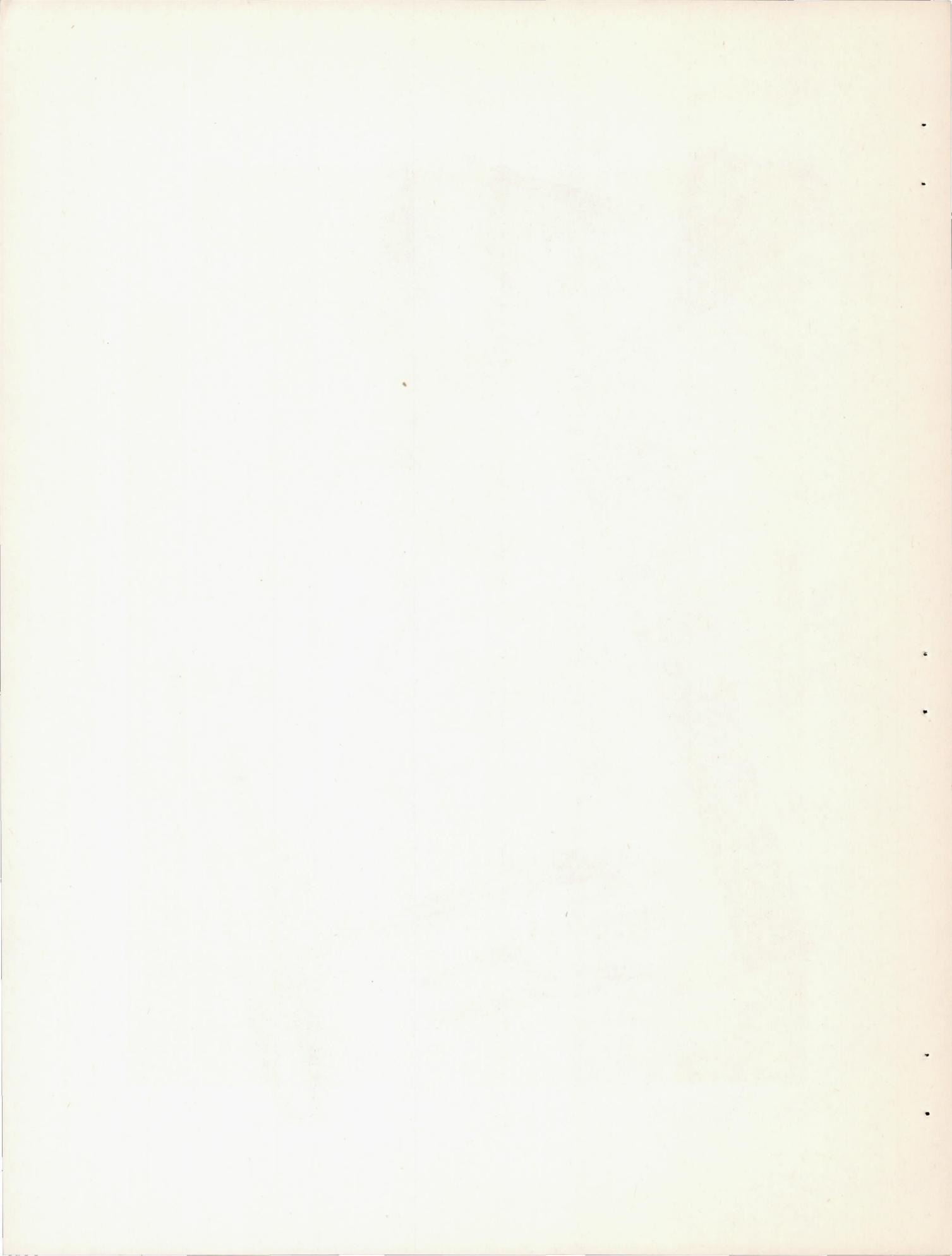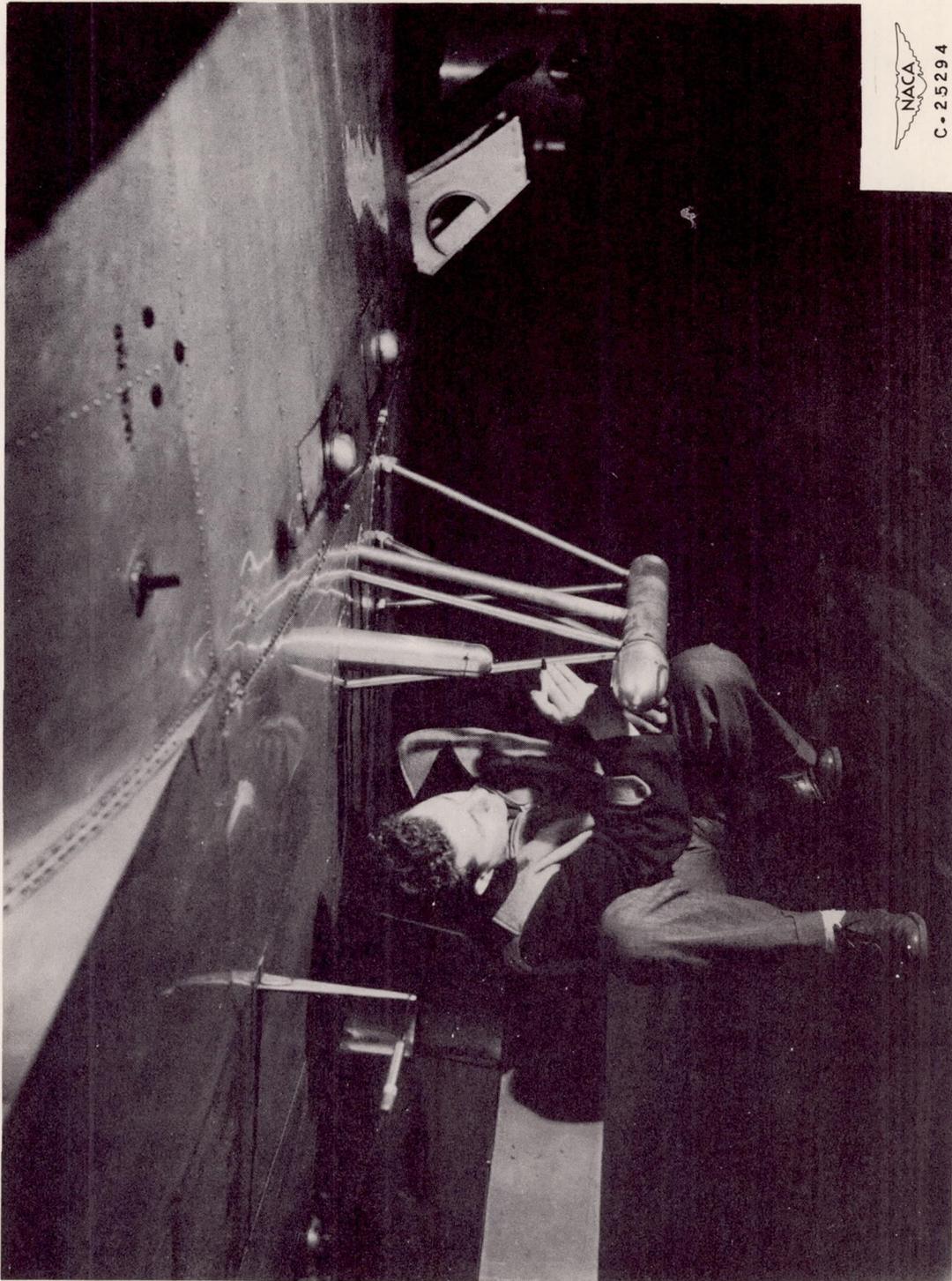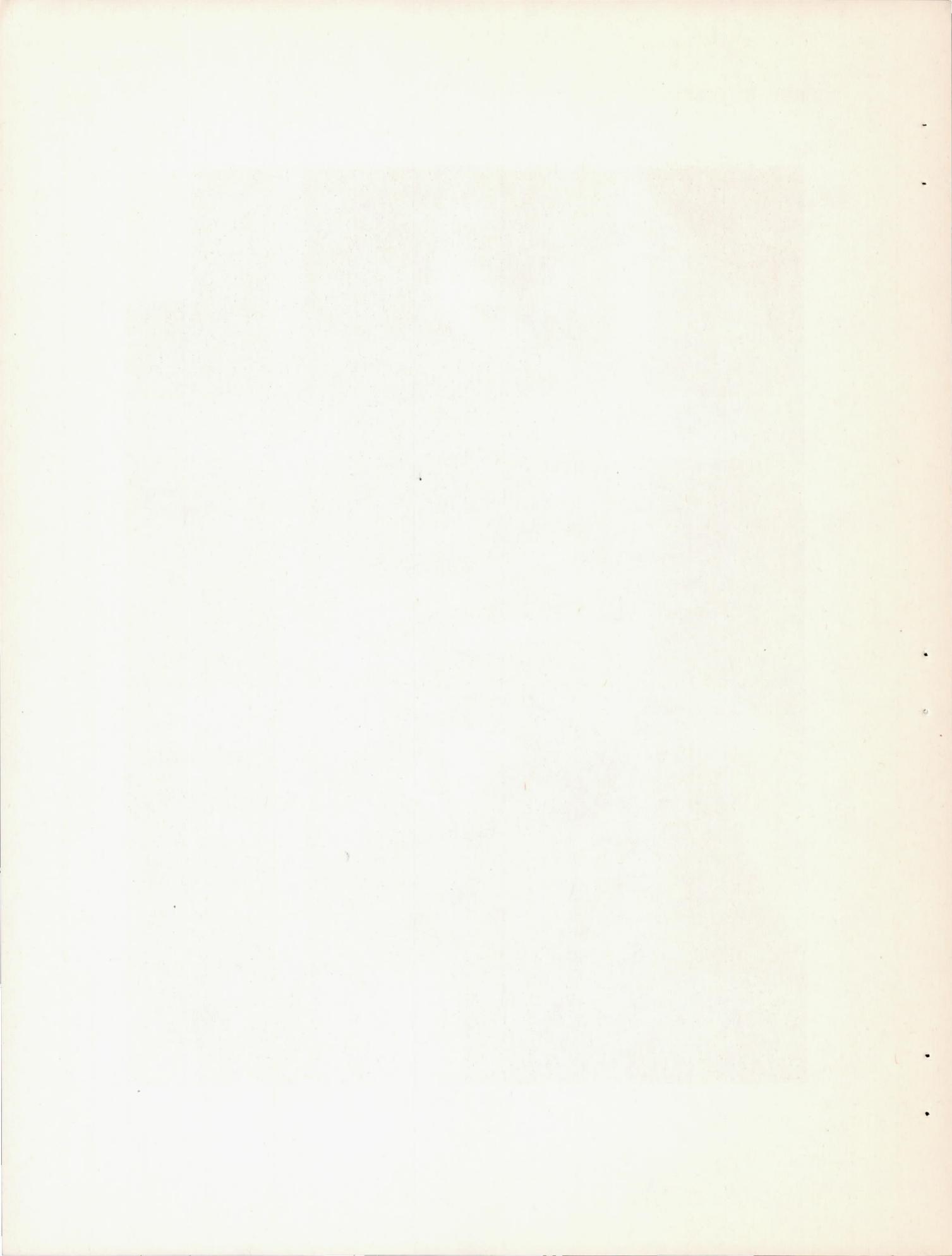Figure 4. - Pulsing unit and light-source holder of droplet camera.

Figure 5. - Circuit diagram of droplet camera.

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Figure 6. - General view of droplet camera.

Figure 7. - Droplet-camera mounted on airplane.
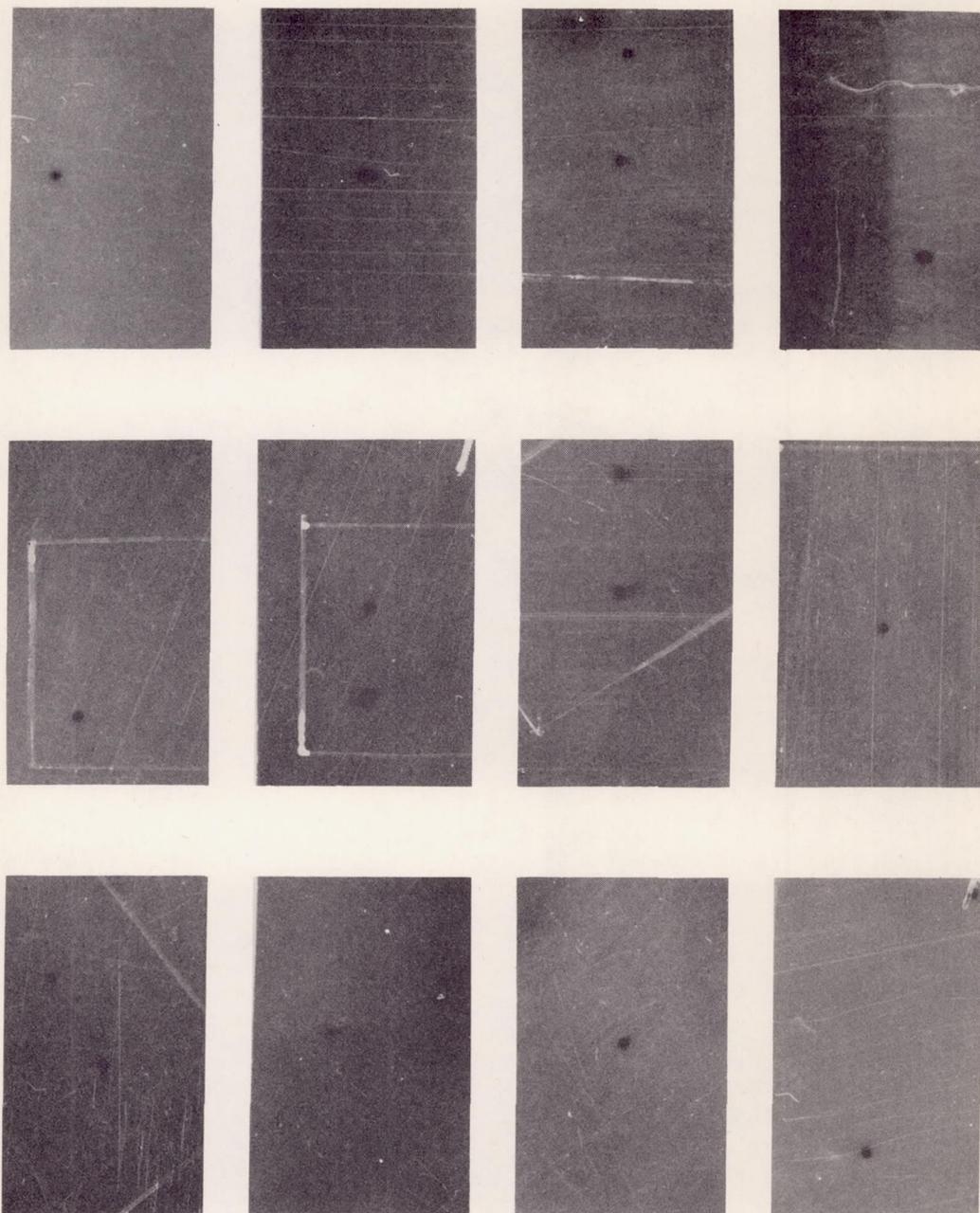
Figure 8. - Photographs of cloud droplets taken in flight with droplet camera.   Portions
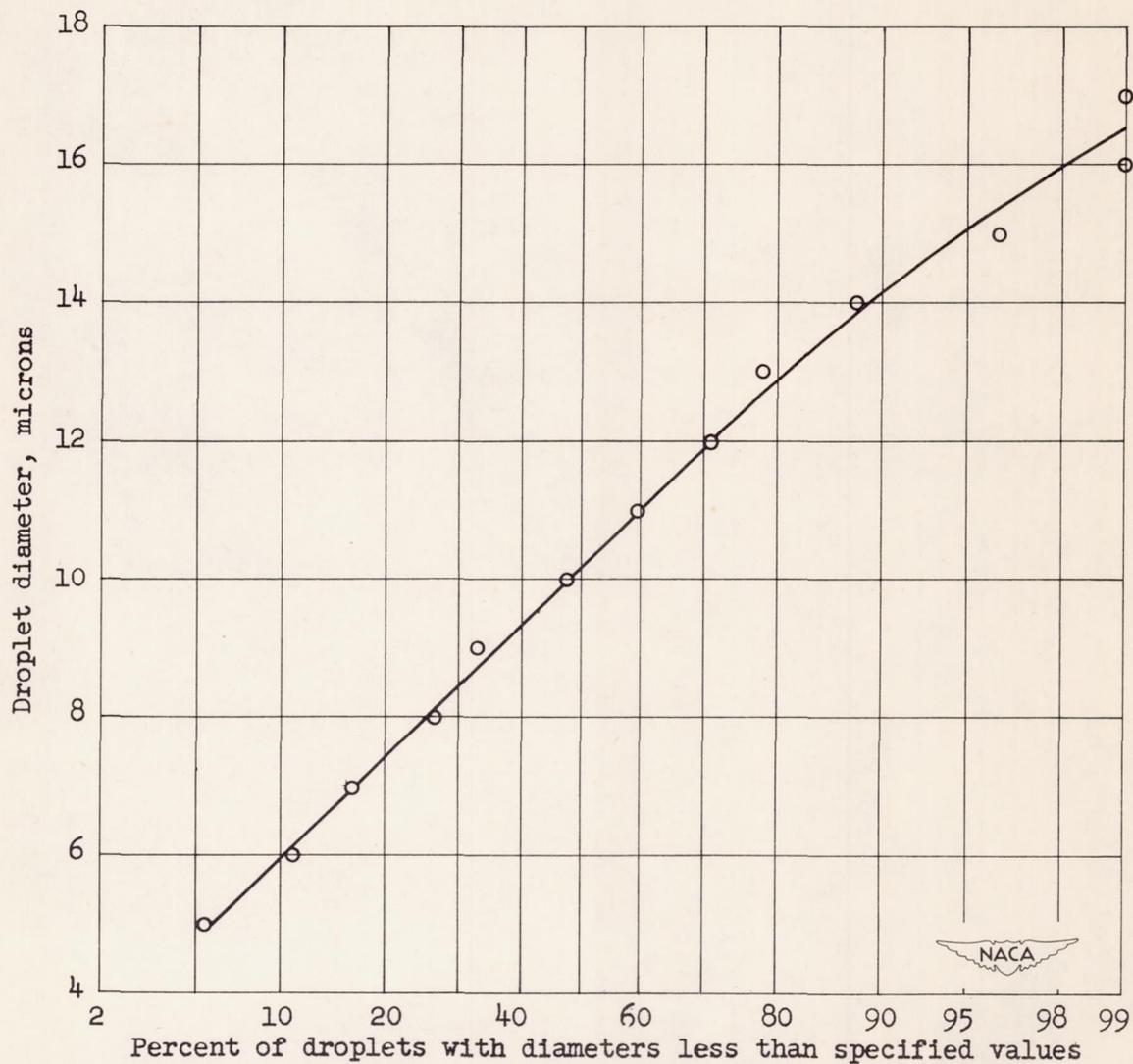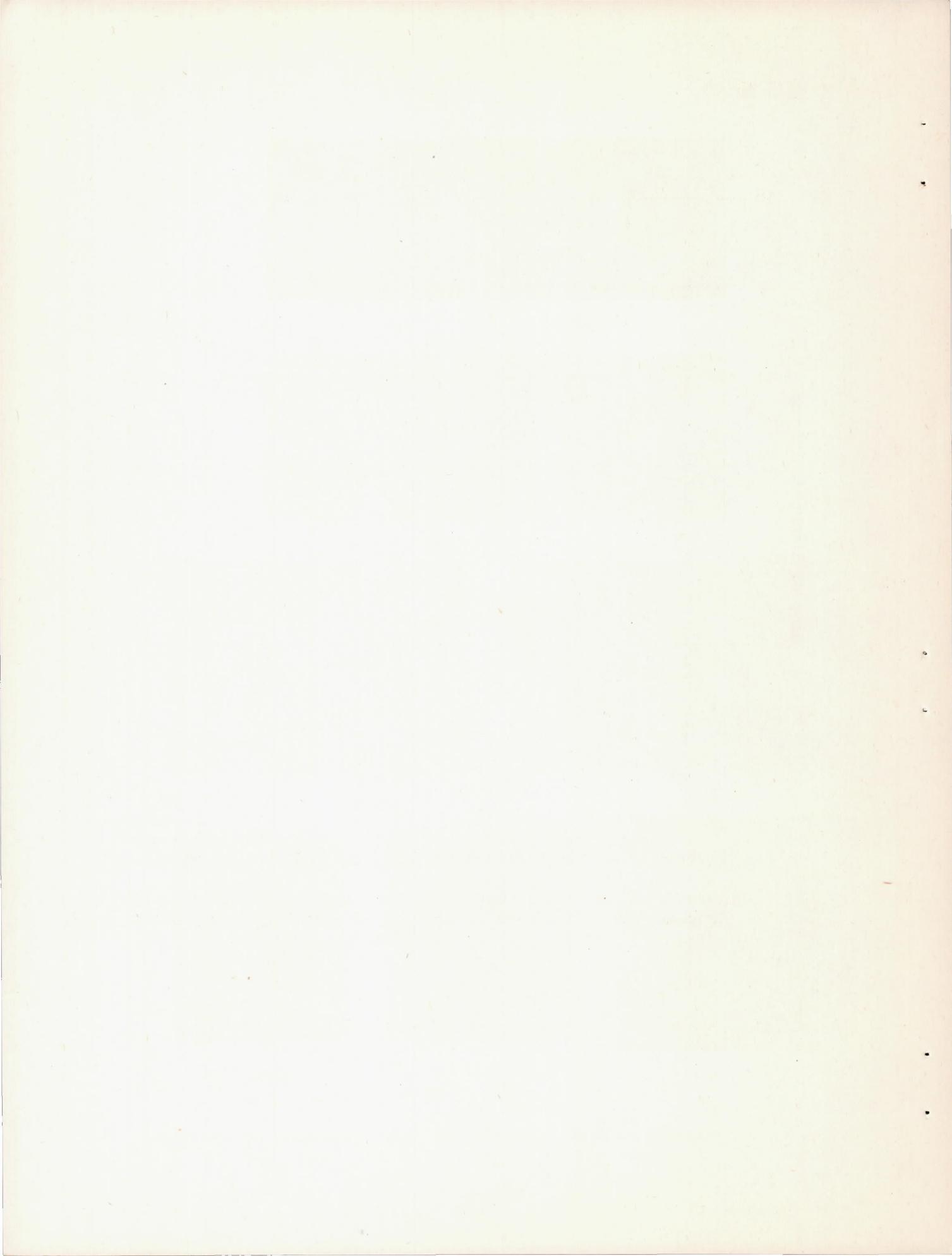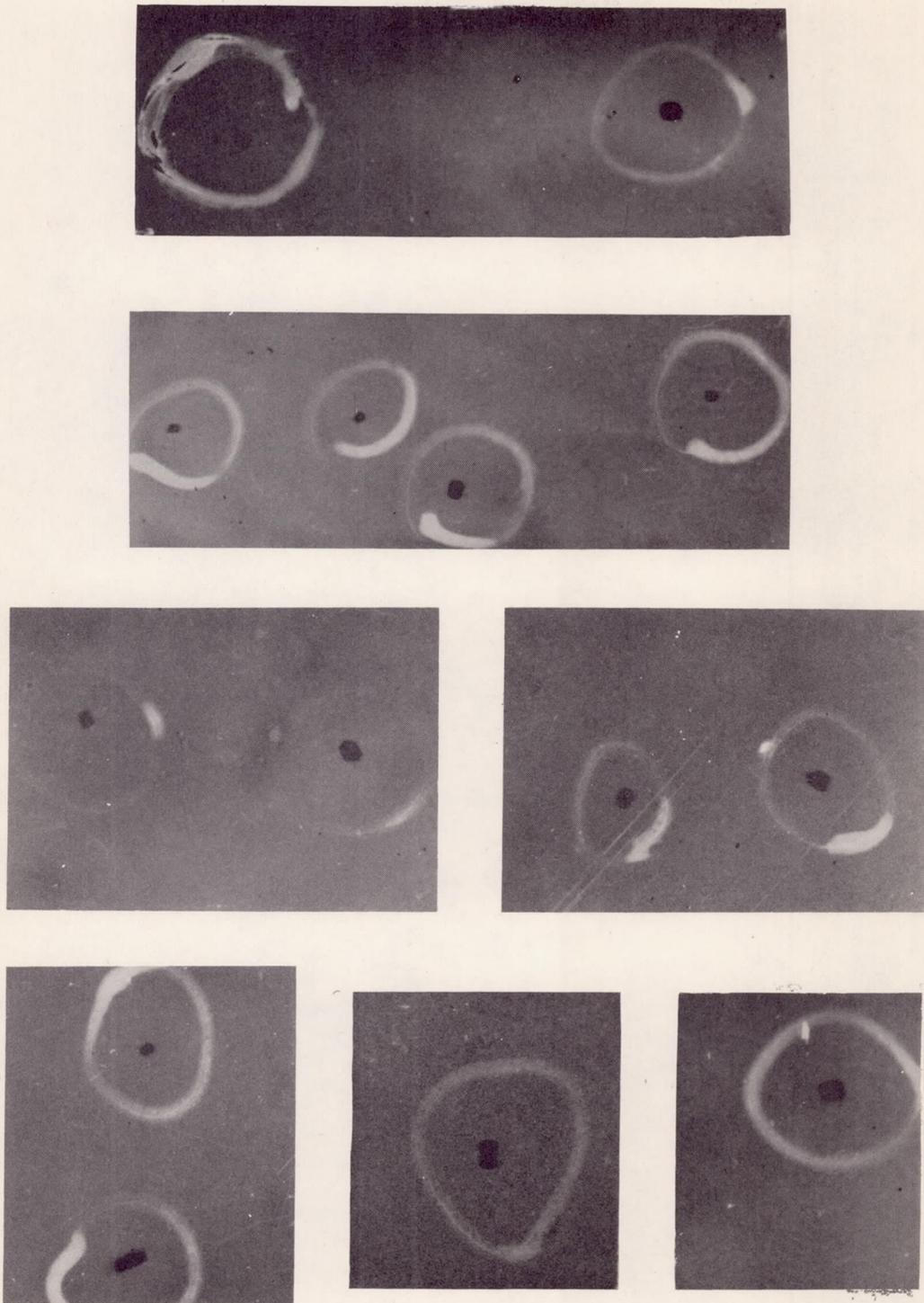are from several negatives and enlarged approximately 3 times.
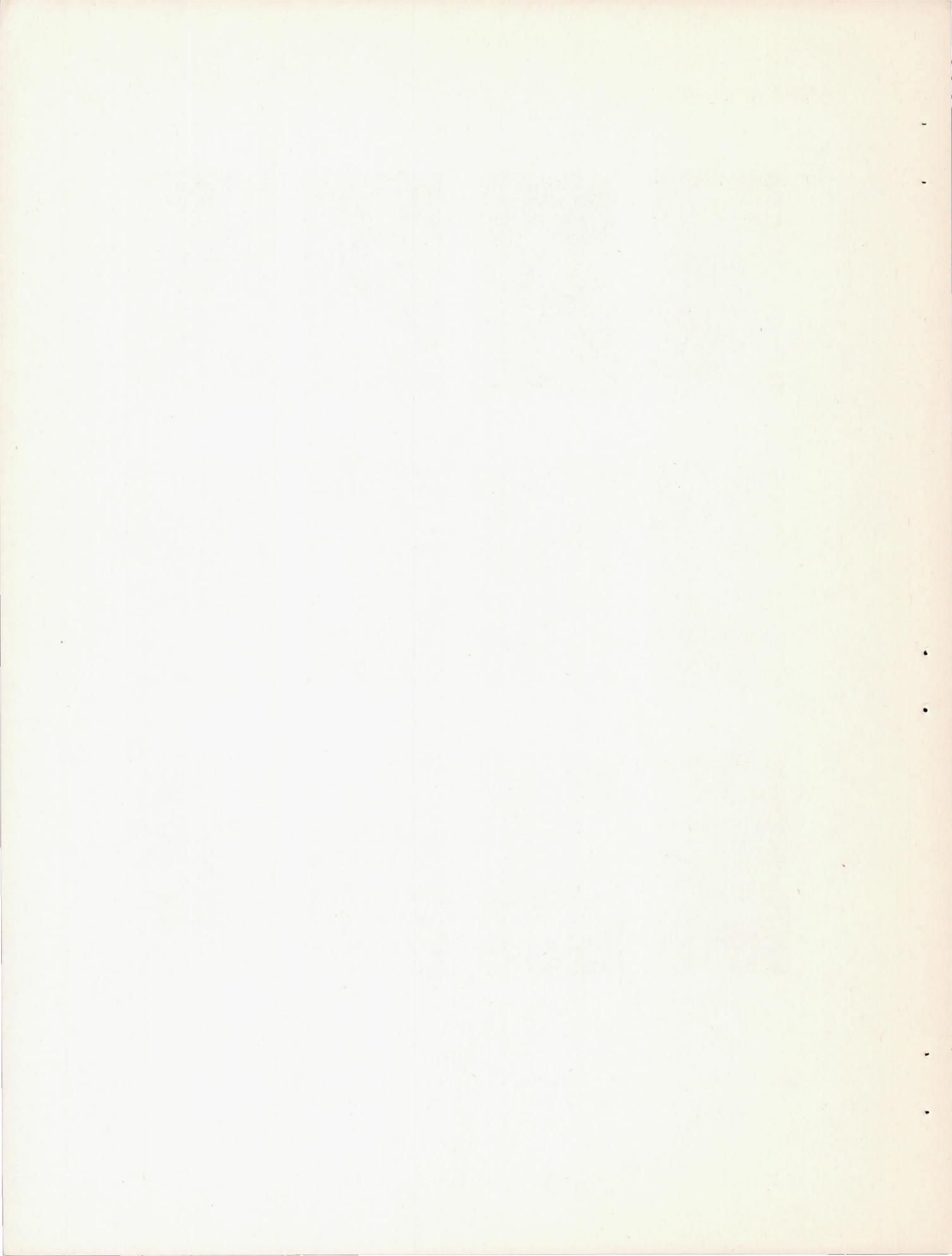
Figure 9. - Cumulative-frequency curve showing distribution of droplet sizes in a cumulus cloud as measured from droplet-camera photographs.

Figure 10. - Ice crystals suspended in cloud chamber as photographed by droplet camera.