ROCKET-BORNE INSTRUMENTATION FOR THE MEASUREMENT OF ATOMIC OXYGEN BASED ON CHEMICAL RELEASE IN THE LOWER THERMOSPHERE

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Abstract. A rocket-borne instrument to measure mainly atomic oxygen density based on nitric oxide point releases in the lower thermosphere has been developed.

Many of the difficulties associated with these kinds of experiments have been avoided by a new technique ejecting the NO gas in the backward direction of the flight. As a result, shock wave problems are eliminated substantially facilitating measurements and analysis.

Preliminary tests are discussed and construction and mode of operation of the instrument are described. The main advantages of the payload are technical simplicity and low cost. Another factor favouring the method is that it allows determination of the altitude of artificial clouds and of wind speeds with extremely high accuracies. Finally, all observations may be performed using ground-based photographic instruments.

The instrument was flown on three Centaure II-C rockets on 12 and 13 September, 1974. Results, which are presented elsewhere, confirm the usefulness of the experimental concept.

1. Introduction

During the last two decades, a number of rocket experiments to measure the density profile of atomic oxygen in the lower thermosphere has been carried out by several workers.

Atomic oxygen measurements have been obtained mainly by mass spectrometric techniques [1–5] and by using photometry of greenline (557.7 mm) intensity from airglow emission [6–9].

More recently, new techniques have been successfully demonstrated: the silver film oxidation method [10–12], measuring of the infrared bands of the excited hydroxyl radical in the night airglow [13], catalytic probes [14, 15], and rocket-borne OI resonance-scattering systems [16–19]. Although these relatively new methods give satisfactory results, it should be emphasized that most of them are still in a developmental stage and that instrumental improvements are necessary to obtain greater accuracies and higher reliabilities.

The earliest attempts to study the atomic oxygen number density involved the release of nitric oxide from a rocket at night, principally in the 80–140 km altitude region of the atmosphere [20–27]. In this case the determination of $n(O)$ is based on the analysis of the NO–O chemiluminous recombination. In spite of some difficulties inherent in this experimental technique, the main advantage is that only a simple payload is required (a tankful of compressed gas, a timer and an opening system) and that all observations may be realised by ground-based photographic instruments, the light emission produced by the NO–O reaction being sufficiently strong.

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A major problem is the definition of the reaction volume, owing to the fact that the hydrodynamics of the release is sometimes difficult to evaluate. In addition there is only incomplete knowledge of the rate constants for the NO–O chemiluminous recombination and of the reaction mechanism leading to the formation of the NO_2 molecule. As a result, scant quantitative height profile data has been obtained with this method to date.

The present paper describes a rocket-borne instrument based on an alternative release technique largely avoiding the difficulties related to the gas dynamic model. The relatively recent redetermination of the temperature dependence of the NO–O chemiluminescence reaction made by Golomb and Brown [28] was also taken into account in the data reduction [27].

2. General Release Techniques

Chemical releases of liquids and gases have been made principally in single puffs, forming a nearly spherical artificial cloud, in continuous or intermittent trails creating a cylindrical injection zone. This injection technique permitted highly successful measurements of winds and diffusion from the motion and growth of the artificial cloud; determination of temperature, composition and chemical processes from emitted or scattered radiation; and the study of the relation of neutral and ionized species and of magnetic and electric fields [29, 30].

The primary requirement for a release material is that it leads to an illumination process which, on one hand, is intense enough for detection and, on the other hand, is sufficiently long lived for observation. Most ejections are carried out in a controlled way along the ballistic trajectory of a rocket. Trail formation may be realised by different techniques but generally the gas or liquid is released through an orifice selected to give the desired rate of injection. It is opened by means of cartridge-actuated valves initiated by a programming unit.

Technically, trail releases are relatively complicated. The orifices sometimes freeze and, consequently, ejection is not always stable and continuous as a function of time. The main advantage, however, is that very accurate and detailed vertical measurements over a large altitude range may be obtained. Furthermore, the lack of explosive charges is a supplementary factor in favour of this method and increases the reliability of the payload.

Point releases are usually made by explosive cords cutting the gas containers, or by more complicated pyrotechnic release mechanisms. In both cases, the explosive charge can be initiated electrically (squibs, igniters and detonators) or by mechanical initiator units, the time delays being predetermined by a timer or by a miniature switch.

The technical concept of a point release is relatively simple and much easier to realize. A major argument for the choice of this method is related to an observational aspect, for all observers the nearly spherical artificial cloud provides a similar optical thickness, whereas in the case of a trail release, only the observer pointing into the direction of the trail axis profits from a maximum optical thickness. It follows that the results obtained from of point releases are much easier to interpret.

Generally, the payload consists merely of a tankful of compressed release material, a timer, a mechanical structure for the fixation of the container(s) and an opening system.

As already mentioned in the introduction, the release of nitric oxide from rockets into the upper atmosphere can be used to determine ambient atomic oxygen concentration. It should be noted that absolute numerical values for the number density as a function of altitude have only been obtained when nitric oxide was released continuously or intermittently [21–25]. Moreover, the technique always consisted of releasing a jet of NO in the forward direction of the flight, generating a hemispherical mixing zone in front of the rocket bounded by an inner and a bow shock. As a result, analysis of the glow was extremely difficult also requiring complicated gas dynamic considerations.

In recent years, the problems with the hydrodynamics of the release and the rate constants have been partially avoided by introducing theoretical gas dynamic models [21] and by simulating the upper atmosphere nitric oxide release in a series of wind tunnel experiments [23]. Photometers located near the release orifices, viewing a small portion of the flow from its center and telemetering the observed radiance during the flight have also improved and simplified the gas dynamic analysis [24, 25].

In spite of all these improvements the nitric oxide release method did not become a widely accepted technique mainly due to the difficulties mentioned above.

When we planned our chemical seeding experiments launched in 1974 from the CNES launching facilities in Kourou (French Guyana), the primary objective was to build a simple technical nose cone device. All data-gathering instrumentation had to be ground-based and the analysis of the results had to be easy to evaluate.

3. Preliminary Tests

The qualification model was submitted to a number of severe tests proving the reliability of all mechanical, electrical and electronic units.

The nitric oxide was contained in four liter cylindrical aluminium containers manufactured by the Société Métallurgique de Gerzat (France). The gas pressure was 50 atm. Consequently, the total amount of the released gas per bottle was 268 g, corresponding to approximately 5.4×10^{24} molecules.

In order to obtain a hydrodynamic picture easy to evaluate we decided to use point releases and to release the NO-jet into the backward direction of the flight with a speed comparable to the velocity of the rocket. As a result, the absolute speed of the flow remained subsonic not creating shock waves. The latter condition required head separation between the nose cone and the rocket motor.

The payload was essentially composed of four bottles (length: 684 mm; inside diameter: 102 mm; thickness of the bottom $\simeq 7$ mm) to be opened at four different altitudes in the 80–105 km region by means of a pyrotechnic release mechanism.

The principal technical problem of the payload consisted of the development, adjustment and qualification testing of the opening system.

A point or instantaneous release requires the formation of a hole as large as possible and, consequently, a relatively high amount of explosive charge is needed. On the other hand the explosive charge has to be kept at a minimum to avoid that detonation of one container damages the opening systems of the remaining ones. It is clear that the design of the release mechanism represents a compromise between these two conflicting requirements.

To fulfill the first requirement, an opening system identical to that developed for the S-64 experiment [31 – 35], and employed in two Skylark rockets could have been used. However, this sytem, consisting of relatively small-diameter metal tubing with a core of explosive material for cutting the thin-walled aluminium container could not be retained due to space limitations.

A pyrotechnic system fixed at the bottom of the cylinder to cut a hole of approximately 90 mm diameter was used in five Skua-II flights [36] fired from the launching base of El Arenosilo (Spain) in 1971. From an engineering point of view these experiments, were succesful. However, since the nose cone contained only one bottle, no high safety precautions were required. Because of the available operation facilities and the reliability of this hole cutter, it was decided to produce a similar opening device. The explosive charge, being of the order of 60 g in the previous experiments, had to be sized according to material, thickness and the diameter to be cut also taking into account safe operating conditions as to the other containers.

Various ground experiments and careful selection of size, charge weight, sheath material, cross-sectional shape and stand-off distance finally led to a suitable pyrotechnic system. Filled with a 6.8 g explosive charge, the pyrotechnics were capable of making a hole in the bottles of about 40 mm diameter. More technical details of the metal-cutting release mechanism, developed in collaboration with the Poudreries Réunies de Belgique (PRB) are given in the following section.

Theoretical calculations, confirmed by ground experiments extrapolated to the release altitudes, led to the conclusion that 99% of the total amount of gas would be ejected in less than 0.07 s. In the 80–105 km altitude range, this corresponds to a release interval of about 60 m, the sounding rocket moving at a typical velocity of approximately 1000 ms^{-1}. This result reveals that an opening of 40 mm satisfies the principle of a point release, the initial Gaussian radius of the artificial cloud being 60 to 70 m.

The pyrotechnic system as well as the electronics must be capable of withstanding shock and vibration induced by the explosion of the previous containers.

In order to protect the pyrotechnics from the shock wave generated by the opening of the first bottle, a shield consisting of three stainless steel coaxial cylindrical tubes was placed around the release mechanisms.

The electronic components were isolated from the mass of the rocket by means of

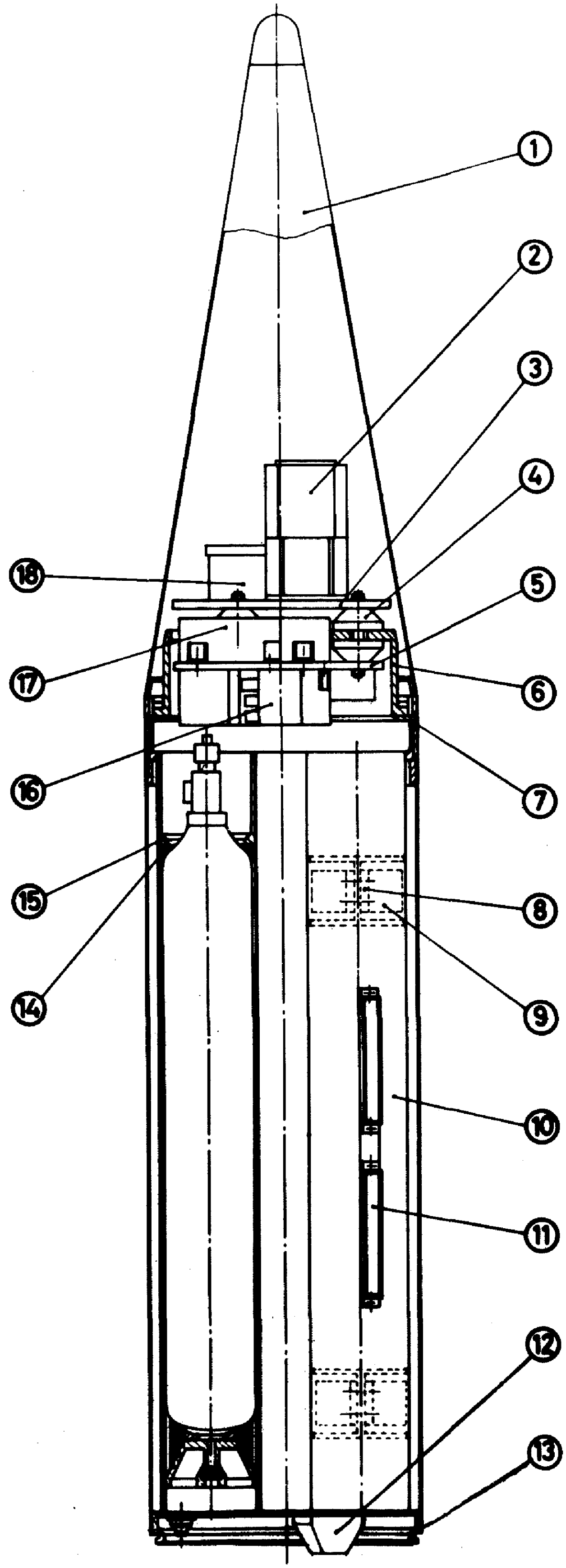

Fig. 1. Schematic view of the NO-II payload. 1. Nose cone. 2. Security box. 3. Upper plate. 4. Shock-mounts. 5. Lower plate. 6. Intermediary plate. 7. Upper bulkhead. 8 and 9. Attachment ring. 10. Cylindrical pipes for the mounting of the bottles. 11. Explosive actuated miniature switch. 12. Mechanical stop unit for the preloaded spring system. 13. Lower bulkhead housing two manacle units. 14. O-ring seal. 15. Stop flange ring. 16. Batteries. 17. Timer. 18. Radar transponder. The pyrotechnic devices used to make a hole in the containers are fixed at the bottom of each cylinder.

3 pairs of Vibrachoc shock-mounts (Figure 1) mounted at 120° to an intermediary plate (6). The shock absorbers (4) support two circular mounting flanges: an upper plate (3) carrying a radar transponder (18) and a security box (2), a lower plate (5) containing a timer (17) and batteries for the detonators, as well as the explosive actuated miniature switches and the electronics.

To evaluate the reliability of the electronic parts after ejection of the gas of the first container, ground simulations of the explosion were carried out at the PRB range in Leopoldsburg (Belgium) with a prototype of the payload. Shocks on the order of 4000 g were measured by pressure transducers attached to the lower bulkhead of the payload structure. The extremely short time intervals could not be precisely determined, but it was found that they were much less than 1.0×10^{-3} s. Taking 1.0×10^{-3} s as an extreme value the corresponding acceleration transmitted to the vibrating system containing the electronics and taking into account the transmissibility of the Vibrachoc shock-mounts yields about 400 g.

The timer not being capable of withstanding shocks up to 400 g, it was decided to use explosive-actuated miniature switches, hermetically sealed in a bronze housing, for the successive gas releases. However, the timer was retained for separation between payload and rocket, for opening of the first container and for initiation of the miniature switch train. The input signal for the latter started before creation of the first artificial cloud.

The miniature switches, constructed by Atlas Chemical Industries, Aerospace Division, are qualified to withstand shocks of 2000 g, 1.5×10^{-3} s. Assuming as a limiting value a time interval of 1 ms the calculated impulse transmitted to the switches is about 35% above the maximally allowed impulse. Theoretically, therefore their use is not without risk. However ground testing showed that the switches are reliable since no failures were experienced.

A prototype of the payload as well as the three flight models were subjected to a series of sinusoidal and random vibration [37, 38] at the laboratories of SOPEMEA (Société pour le Perfectionnement des Matériels et Equipements Aérospatiaux), Toulouse, France. All vibrational tests, carried out in accordance with Dragon A and B specifications, gave satisfactory results.

4. Flight Instrument

An overall schematic view of the flight instrument was given in Figure 1.

4.1. Mechanics

A standard Centaure non-skirted nose cone (1) and a cylindrical skin cover the flight instrument. The non-ejectable nose cone, made of 1 mm stainless steel, is fixed to the upper bulkhead (7) of the cylindrical part by high-grade screws. Four cylindrical tubes (10), holding the gas containers by means of attachment rings (8, 9), are inert gas welded to the upper (7) and lower (13) bulkhead. The internal part of the cylindrical pipes is equipped with a stop flange ring (15). An O-ring seal (14), slipped over the filler-neck of the bottle and placed to the stop flange ring, absorbs an important quantity of the energy induced at the moment of explosion. Connectors for the power supply of the release mechanism and two mechanical stop units (12) for the preloaded spring system are mounted on the lower bulkhead (13), also housing two manacle units.

After the manacle rings have been jettisoned at about 65 km through explosive bolts, the preloaded spring system is released and propels the payload with a speed of more than 2 ms^{-1}. This separation allows free expansion of the nitric oxide.

The three shock-mounts (4), attached to the intermediary plate (6), support the upper (3) and lower plate (5). The batteries (16) and the timer (17) are placed on the lower plate; the upper plate carries the radar transponder (18) and the security box (2).

The cylindrical skin is provided with openings for two radar antennas, for a receptacle for safe-, test- en arming plugs and for an umbilical connector.

Finally, two manacle units housed in the lower bulkhead (13) ensure fixation of the payload to the rocket engine.

Figure 2 gives a cross-section drawing of the opening system, while Figure 3 shows a partial view of the release mechanisms prior to the vibrational tests.

The three basic parts of the pyrotechnic devices are respectively the protector, consisting of three stainless steel coaxial cylindrical tubes, the body charge containing the cone, explosive charge and the pellet booster, or primer, and the detonator holder containing the electric detonator, the holder short circuit and the plug short circuit.

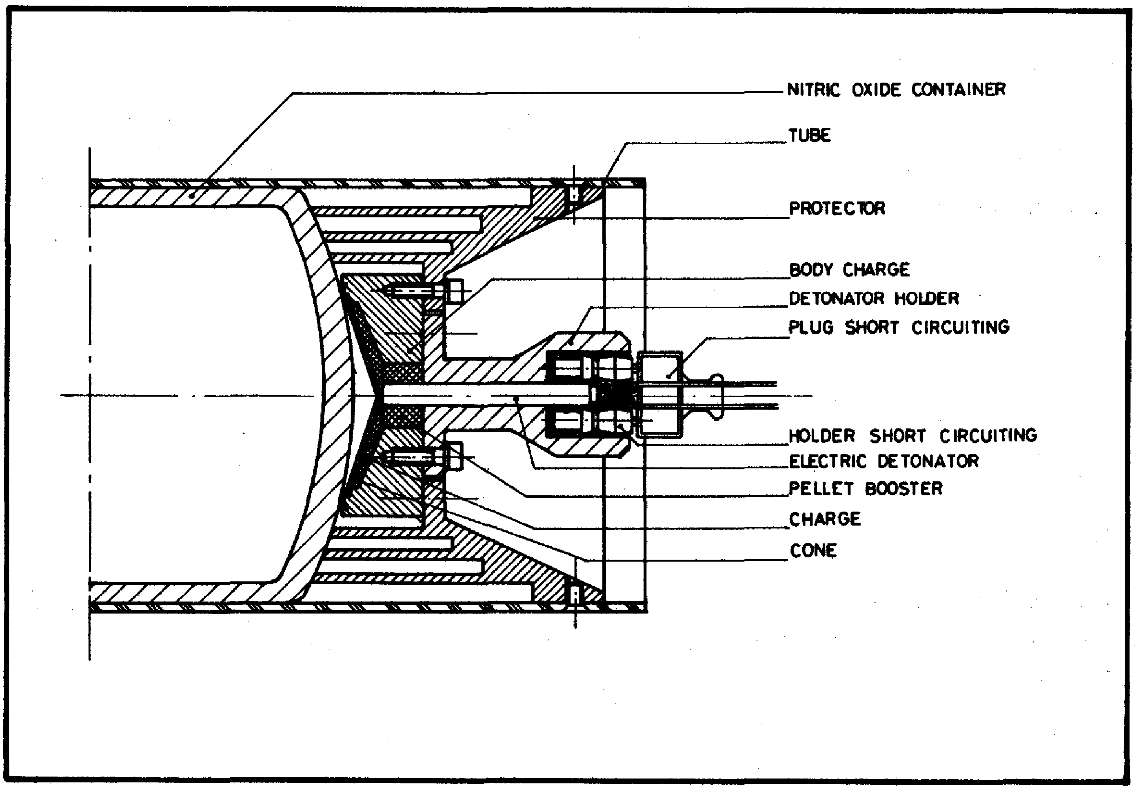

Fig. 2. Cross-section drawing of the pyrotechnic opening system.

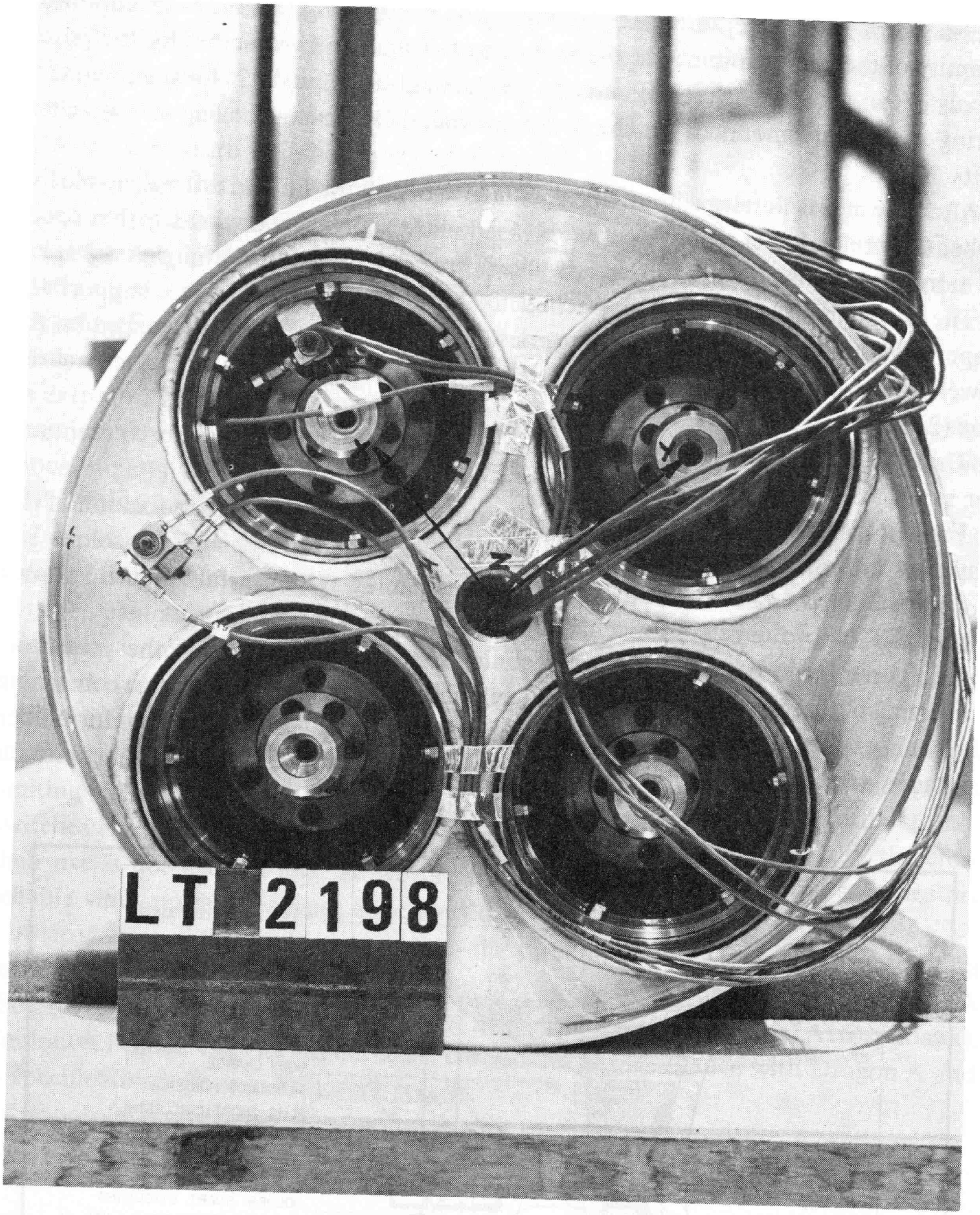

Fig. 3. Lower part of the NO-II payload showing the pyrotechnic opening systems. One can also see two triaxial vibration pick-ups measuring the acceleration levels during the vibrational tests.

A detailed description of the characteristic features and operation of the explosive train is beyond the scope of this paper. We only mention that the primer is the first explosive material ignited and is used to detonate of the less sensitive and more stable explosive charge.

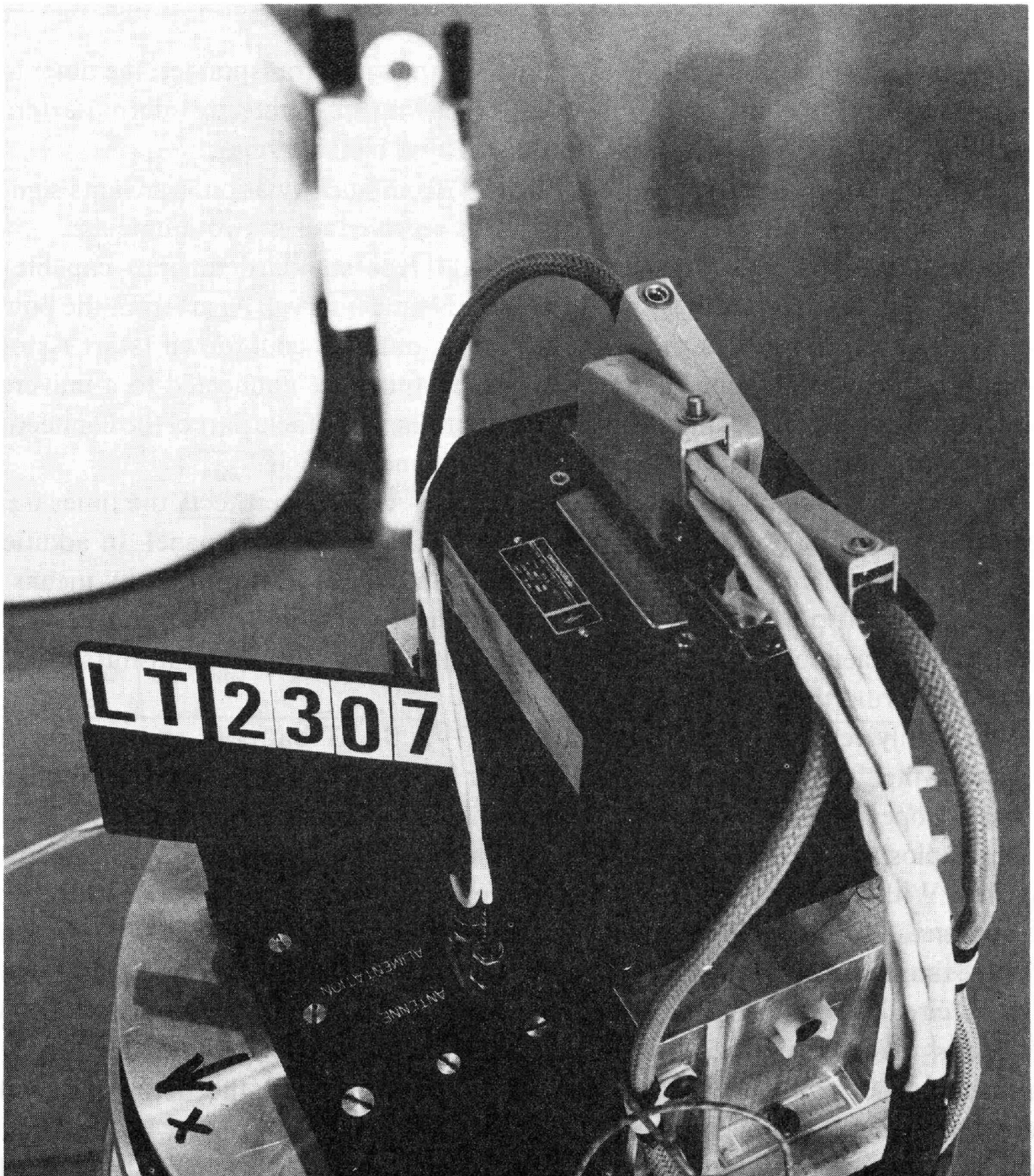

Fig. 4. Upper part of the NO-II payload, with nose cone removed, showing the upper plate with the radar transponder (left) and the security box (right). One of the Vibrachoc shock-mounts is partly visible below the upper plate.

4.2. Electronics

The onboard battery set, supplying the power for the radar transponder, the timer and the security box, is composed of 14 SAFT type VR 1.2 elements. Internal-external switching of the power supply can be realised by a bistable relay.

The RR 104 type radar transponder (Figure 4) from Sud-Aviation, transmits signals automatically when the proper interrogation is received, uses two antennas.

Constructed by Crouzet Laboratories, the 11 type standard timer is capable of initiating 5 flight sequences in a 0 to 1023 seconds time interval. Apart from the power supply, the timer comprises the following major outputs: countdown (start + stop), resetting to zero and testing of the clock. The outputs are connected to a universal check out unit by means of an umbilical connector, the receptacle part of the connection system being incorporated into the wall of the launch vehicle.

The security box (type BS.5), developed by Sud-Aviation, protects the timer input signals by a bistable relay (Ledex) controlled by the test-control panel. In addition, this electronic unit contains a 3.5 s timer that can only be switched on by means of a spring metal strip opened by pulling the umbilical connector at the time of rocket lift-off. This timer forms a supplementary security inhibiting any transmission of a command during the 3.5 s time interval.

Eight highly reliable nickel-cadmium type GVB SAFT batteries are used for the ignition of the detonators and the pyrotechnic devices. If the ignition of a detonator causes an open electric circuit, the corresponding battery is re-used.

The explosive actuated miniature switches are manufactured by ICI Aerospace Division. With a preset time delay of approximately 6 s, these units are characterized by compactness, lightweight, small size and high reliability.

Three timing circuits comprising two in miniature switches in series were used. Each of these circuit was made fully redundant guaranteeing a high degree of reliability.

The first switch (Figure 5) is initiated 6 s before opening of the first container and starts a second explosive-actuated device. The latter ignites the detonator of the second bottle, also energizing the pyrotechnic train of the third bottle. It follows that the time delay between the opening of the second and the third container is theoretically equal to 12 s. At the same moment, the timing circuit of the last container is actuated. Initiation of the time sequence starts at $H_0 - 30$ s, where H_0 is the time of rocket lift-off. In Figure 5 the time scale represents the time delay, where $\Delta T = 0$ corresponds to the switch on of the timer.

Five double-bridged detonators are used: one for the head separation, the other for the opening systems of the bottles. Each igniter is provided with a short circuit plug (removed shortly before launching), protecting the explosive charge of the pyrotechnics.

As already mentioned, the manacle rings are opened by means of explosive bolts. This operation is not wiring destructive and guarantees, a high impedance between the two leads connected to the corresponding batteries after ignition. As a result the corresponding batteries supplying the necessary current within a very short time interval are not discharged and can be reused for the release mechanism of containers 1 and 2. On the other hand, through the opening of a bottle the body charge and the

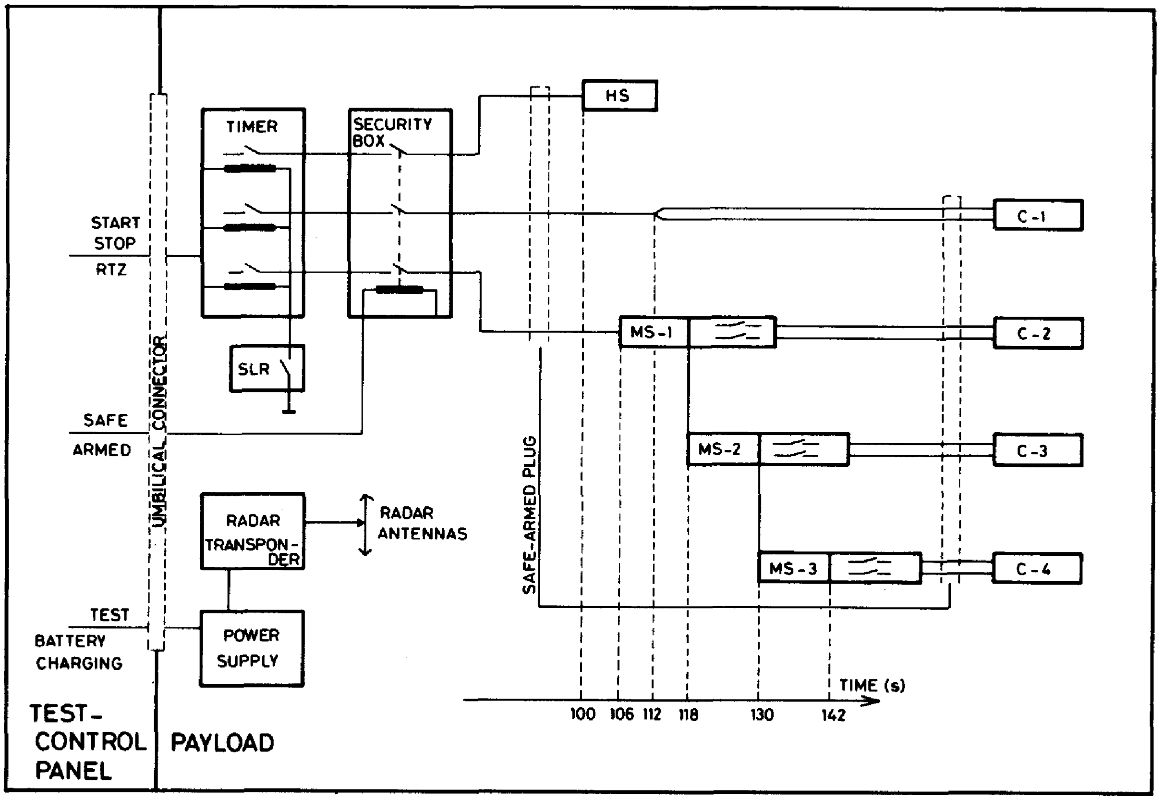

Fig. 5. Simplified block diagram showing also the time sequences during the flight. The following abbreviations are used: RTZ: resetting to zero; SLR: security launching ramp; HS: head separation; MS: miniature switch; C: container.

detonator holder are jettisoned, pulling off the leads of the connector. Consequently an infinite impedance is no longer guaranteed and the batteries that were used for the cutting systems are not re-used.

The timing circuits also contain a receptacle for safe-, test- and arming plugs. By means of the safe plug, the firing lines are separated and the detonators short-circuited. Prior to connecting the armed plug, linking the firing lines with the igniters, a 'no voltage test' is performed on the firing lines and the igniter bridge resistances are measured by a simple test device. With a test plug connected, the timer can be started for checking the monitor signals and switching commands without igniting the pyrotechnics.

5. Data Reduction and Analysis

Three experiments have been carried out, code-named NO-II-1, NO-II-2, and NO-II-3. The payloads were brought to altitude by Centaure II-C rockets launched at night from Kourou, French Guyana (5.2° N, 52.8° W) on 12 September 1974 (two rockets) and on 13 September 1974.

Two kinds of information were obtained from photographic images taken by two ground-based Gianini-cameras ($f = 77$ mm; $f/D = 0.87$) equipped with Kodak 2485 films: (a) the altitude of the artificial clouds and the wind speeds and (b) the atomic density. Although results are presented elsewhere [27, 39, 40] we will briefly mention how wind velocity and atomic oxygen concentration are derived.

A numerical method using a digital computer has been developed to perform the triangulation necessary for the determination of the release positions [34, 35, 41].

Stars recorded on the same films as the artificial clouds are used to determine a set of standard co-ordinates corresponding to the position of the measured stars on the celestial sphere. The relation between the standard co-ordinates and the measured rectangular co-ordinates can be expressed by a polynomial transformation, the a priori unknown coefficients of this relation, the so-called plate constants, being calculated by a least square method. The equatorial co-ordinates (right ascension and declination) of the center of the artificial clouds, chosen on simultaneous photographs taken from two or more observing sites may now be determined, taking into account the results of the plate reduction study. Finally, the knowledge of the geographical position of the camera sites allows the computation of the altitudes of the point releases.

The wind speeds are derived from the motion of the artificial clouds by dividing the measured distance, calculated from two position measurements, by the corresponding time interval.

Although essentially intended for isodensitometrical studies, the Gianini cameras have proven to be high quality triangulation instruments. Altitudes are obtained with an accuracy of the order of (40 ± 10) m whereas wind speeds can be deduced with an accuracy of the order of 1 m s^{-1} for time intervals from 30 to 50 seconds between two successive position determinations of the clouds. To the best of our knowledge, similar precisions have never been reported.

As already mentioned the determination of the atomic oxygen concentration is based on the analysis of the light intensity radiated by the NO release. A detailed description of the procedure is given in a previous paper [27]. According to this work, the atomic oxygen number density $n(\text{O})$ can be expressed as

$$n(\text{O}) = I/[I_0^a n(\text{NO})] \tag{1}$$

where I_0^a is the best fit expression of the photon emission rate coefficient ($\text{cm}^3\ \text{s}^{-1}$) of the NO–O chemiluminous recombination as given by Golomb and Brown [28], $n(\text{NO})$ is the number density of nitric oxide, which is obtained from the total amount of the ejected NO particles and from the mean radius of the artificial clouds calculated by means of a Joyce and Loeble double-beam recording isodensitometer. I is the total number of photons (photons $\text{cm}^{-3}\ \text{s}^{-1}$) emitted per unit time and per unit volume.

Finally, the expression of I, derived from the total quantity of light energy deposited on the films and determined from isodensity traces of the photographs and by means of relative and absolute film calibrations, may be written as

$$I = 5.907 \times 10^{-19}\, [r_e^2 L(0) S_R^2 / Vt] \sum_{i=1}^{13} [P_i \varepsilon_i / T(A)_i T(G)_i]\ (h\nu\, \text{cm}^{-3}\, \text{s}^{-1}) \tag{2}$$

where the various symbols are defined as follows:

r_e: the Gaussian half-width, i.e. the distance on the densitometric recording image at which the radiant exposure is $1/e$ times the peak value
$L(0)$: the radiance in the center of the image
S_R: the slant-path, i.e. the distance between the camera and the artificial cloud
V: the reaction volume of nitric oxide
t: the exposure time of the film
ε_i: the energy conversion factor (Joule $\rightarrow h\nu$) for the i_{th} wavelength interval ($i = 1, \ldots, 13$)
$T(A)_i$: the atmospheric transmission coefficient from sea level to space
$T(G)_i$: the camera lens transmission coefficient
E_i: the relative luminous intensity of the emitted NO–O spectrum
S_i: the adopted relative spectral sensitivity of the film
P_i: $E_i S_i / \Sigma E_i S_i$.

Resulting atomic oxygen densities as calculated from expression (1) are presented by Van Hemelrijck [27]. The data are obtained from 66 isodensity traces of 2 or 5 s exposure photographs. A calculated uncertainty level, based on an error analysis of each measurement, was assumed to be $\pm 30\%$.

As an example, Figure 6 gives a magnification of a typical photographic image showing two artificial clouds of the NO-II-3 experiment.

6. Advantages and Future Developments

From an analysis of all reported nitric oxide releases [20–26] it follows that it is necessary to take into account the mixing layer between the inner shock and the bow shock generated by releasing the NO-jet into the forward direction of the flight. Our experimental technique, using point releases and ejecting the gas into the backward direction, represents an important advantage since the absolute speed of the flow remains subsonic without the creation of a shock wave. The problems with the gasdynamic model are thereby eliminated, considerably facilitating measurements and analysis.

The feasibility advantages of the NO-II experiment, compared to other methods recently developed [10–19] are the relative simplicity and low cost of the payload as well as the visual display, allowing all observations to be made by ground-based photographic equipment. Another factor favouring the present technique is that the measurements of the altitudes and the winds may be realised on the same photographic images as those used for the n(O) determination.

Since the containers used in this experiment were rather voluminous, the number of point releases per rocket was limited to four. Analysis of camera data shows that around 80 km the minimum detectable radiated power is of the order of 5 Watt, corresponding to a global emission rate of approximately 1.6×10^5 Rayleigh [27]. For

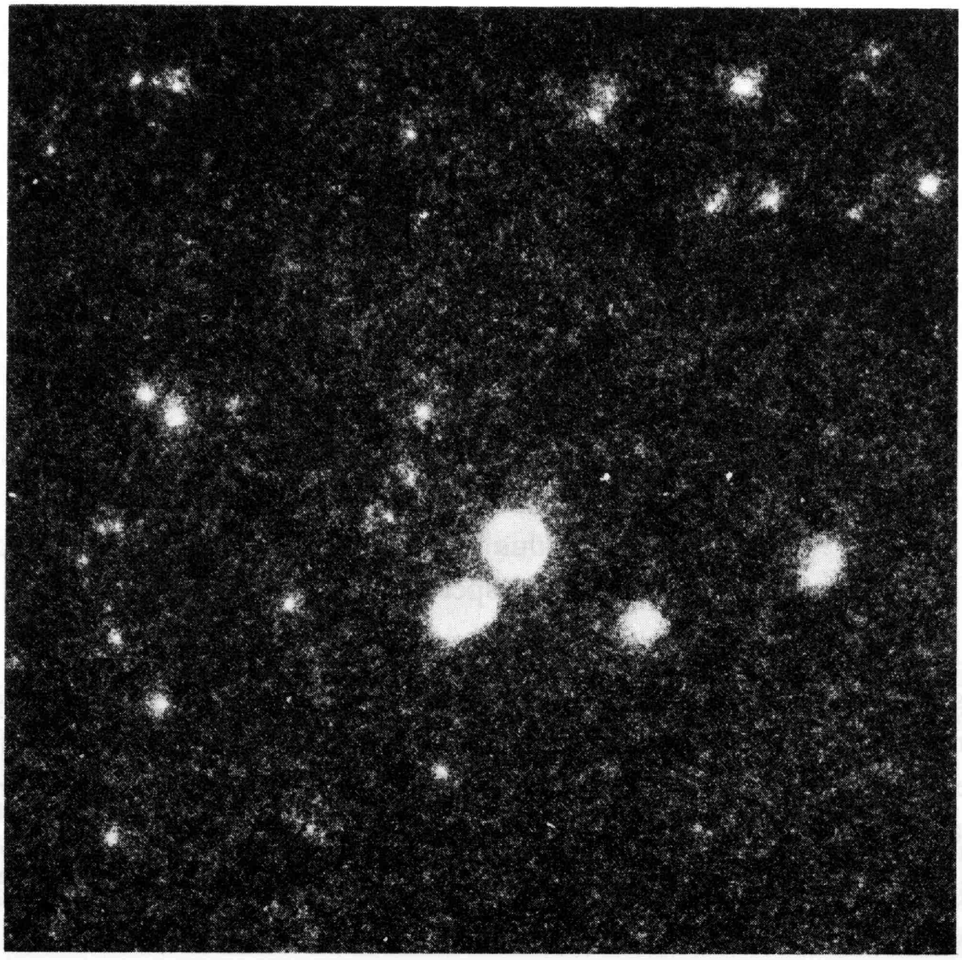

Fig. 6. Five-second exposure photograph (magnification ≅20×) of two nitric oxide point releases of the NO-II-3 experiment. The artificial clouds (nearly circular in shape) are visible in the center of the image. Note also the presence of various stars under the form of luminous spots.

comparison, typical radiant flux values measured at release altitudes between 85 and 105 km ranged from 100 to 200 Watt. These findings led to the conclusion that the total amount of released gas, being 268 g per bottle in the NO-II experiment, could be decreased at least by a factor of 10. Consequently, the containers may be made with dimensions much smaller than those reported here, thus enhancing the total number of point releases per flight.

7. Conclusions

The NO-II rocket-borne instrumentation, designed and built by the engineering and technical staff of the Belgium Institute for Space Aeronomy, has proven to be a very useful research tool for investigating the lower thermosphere.

Wind speeds [39, 40] and atomic oxygen density values [27] in the 80–105 km altitude equatorial region have been obtained, both from the motion of the artificial clouds and by analyzing the chemiluminescence of the nitric oxide point releases.

Although, some of the techniques could have been improved or modified, the main objective of the NO-II experiment, namely the determination of atomic oxygen density as a function of altitude, was a succes.

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