NASA TECHNICAL MEMORANDUM NASA TM-75382

APPLICATION OF MULTISPECTRAL COLOR PHOTOGRAPHY TO FLAME FLOW VISUALIZATION

G. Stoffers

(NASA-TM-75382) APPLICATION OF MULTISPECTRAL COLOR PHOTOGRAPHY TO FLAME FLOW VISUALIZATION (National Aeronautics and Space Administration) 33 p HC A03/MF A01 CSCL 14E G3/35

N79-19315

Unclas 16392

Translation of "Anwendung der Multispektralfotografie zur Sichtbarmachung von Flammenstrukturen," Deutsche Forschungs-und Versuchsanstalt fuer Luft-und Raumfahrt, Brunswick, West Germany, Report DLR-MITT-74-23, May 1974, 31 pages

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 FEBRUARY 1979

APPLICATION FOR MULTISPECTRAL PHOTOGRAPHY FOR FLAME FLOW VISUALIZATION

G. Stoffers
German Institute for Aeronautics and Space Research and Development

Summary /4*

For flames of short duration and low intensity of radiation a spectroscopical flame diagnostics is difficult. So, in order to find some other means of extracting information about the flame structure from its radiation, the feasibility of using multispectral color photography was successfully evaluated. Since the flame photographs are close-ups, there is a considerable parallax between the single images, when several cameras are used, and additive color viewing is not possible. As, for this reason, each image must be analyzed individually, it is advisable to use color film in all cameras. One can either use color films of different spectral sensitivities or color films of the same type with different color filters. Sharp cutting filters are recommended.

---

*Numbers in the margin indicate pagination in the foreign text.

Content Page /5

1. Introduction

/6-7

The use of flame spectroscopy appears to be very difficult without investment of considerable technological effort when investigating flames that burn for a short time only due to the nature of the experiment, and radiate with low intensity. Such flames may appear during supersonic combustion experiments in a wind tunnel with a short run, for instance. To avoid the difficulties mentioned, an attempt was made to gain information about the flame structure from the flame's radiation by means of multispectral photography, employed successfully for aerial photography, in which separate separate pictures are taken for various spectral regions.

To test the applicability and usefulness of multispectral photography test pictures were taken of quite a variety of flames, during an experiment of supersonic combustion, from a hot gas jet with a temperature of about 4500 K, as well as from a plasma jet with temperatures up to 25,000 K.

2. The Method of Multispectral Photography

2.1 Multicamera Systems

In aerial photography four cameras, which are mounted in the same housing, are usually used to take black and white pictures in four spectral areas, using panchromatic film with blue, green and red filters and infrared film with a blank filter. In Fig. 1 sensitivity curves for the two types of film (solid lines) and transmission curves for the filter used (dashed lines) are shown schematically.

Individual pictures are either evaluated densitometrically or, available as diapositives, are projected with one placed on top of the others. Different color filters are placed in front of the projector objective, and the color of the filter used for projection need not agree with that of the filters used to take the picture. The purpose of the filters is to produce color contrasts ,between individual objects shown on the pictures, so great that they can be clearly distinguished from each other.

A normal color photograph also represents a multispectral picture for which individual exposures are taken on different film emulsions in three spectral areas (blue, green, red). The advantage is that the individual pictures are taken through the same objective and from the same position. When using several cameras,which are necessarily in different positions, a certain amount of parallax will exist, however. For aerial pictures the distance between individual cameras is small compared with the object distance, so that parallax can be neglected. With regard to the objectives, differences between individual objectives that are well within manufacturing tolerances can account for certain inaccuracies when several cameras are used. In spite of it, better results are often achieved in aerial photography with several individual pictures in different spectral regions than with a single color photograph. /8

No superposition of individual pictures can be used since the short distance from the object used when taking flame pictures, causes severe parallax errors when several cameras are used. For that reason it makes more sense to use color film for flame photography.

2.2 Use of Color Films

Fig. 2 shows the schematic for color films corresponding to the schematic shown in Fig. 1. The sensitivity curves for the emulsion used in color films are shown. Color film that is sensitive to visible light has three emulsions for blue, green and red light. The initial adjustment of sensitivity of the three emulsions in Fig. 2 corresponds to illumination by daylight. Infrared color film has, in addition to the emulsion sensitive to infrared, two more emulsions for red and green light. Spectral sensitivity is adjusted to the most frequent application of the film, namely agricultural aerial photography, which means light reflected from healthy foliage illuminated by daylight. This light contains, in addition to a green component, a much larger share of infrared radiation. To do justice to it the sensitivity of the infrared sensitive emulsion was reduced somewhat from that of the two other emulsions.

Since, in addition to the emulsion prepared for blue light, all others are also sensitive to blue light they must be protected against it by means of color filters. Daylight color films have a yellow filter emulsion between the blue-sensitive emulsion and the two others. It is represented by the left-hand dashed line in Fig. 2. /9

For viewing through the human eye the infrared light is transformed into red light in the projected picture, red articles are shown as green and green ones as blue.

When it is desired to include all four spectral regions two cameras are required, one of which is loaded with infrared color film the other with daylight color film. The question of illumination is irrelevant in the choice of the film material since the light of the flame itself provides the illumination for flame photography. The use of material that is responsive to artificial light instead of daylight is, therefore, appropriate in reversal film if that corresponds more closely to the flame spectrum.

2.3 Film/Filter Combinations

The possibility was investigated in this case for using color film in combination with various color filters. It was to be determined which film/filter combinations provide the most information and how many individual pictures had to be taken. The result was quite variable for the three experimental set-ups for which test pictures were available.

For the hydrocarbon gas flame, described in Section 3, all essential information is contained in two single pictures, one on infrared color film and one on color film for artificial light. Additional clarification can be achieved with a third photograph, in which color film for artificial light is used in combination with a bright yellow filter having an edge at 420 mm. That way one succeeds in the optical separation of two flame zones that are superposed.

The hot gas jet described in Section 4 is available for an extended time period and is nearly stationary, so that a whole series of pictures can be taken, through various edge filters with closely adjacent filter edges. This makes it possible to assign the radiation recorded by the photograph not only to certain flame zones but also to narrowly limited wave length regions.

Finally, in the third experimental set-up for which test pictures were made, application of the method proved to be less appropriate. This involved a hot gas jet of about 25,000 K, which is very good for spectroscopic analysis but very hard to photograph for various reasons that will be discussed later.

3. Test Pictures During a Supersonic Combustion Experiment

3.1 Experimental Set-up

The first test pictures were taken of the pilot flame of an experiment with supersonic combustion (Fig. 3). The Mach number for the inflow during the experiments was Ma=2.3(Ma=2 for Fig. 5). Static pressure in the undisturbed flow amounted to about 7.3% of atmospheric pressure. Propane was used as fuel for the pilot flame. Boiler ignition cartridges were used for ignition,which contained aluminum and barium nitrate according to information from the manufacturer. The cartridges emit a stream of solid particles as igniter into the flow ,whose radiation is brighter even than that of the pilot flame. Traces of the particles are visible in nearly all of the pictures.

The burning time of the pilot flame corresponds to that of the ignition cartridge (20-30S) and so determines the duration of a test. This time is just about sufficient for taking a series of four to five pictures with the same color filter and changed illumination. The exposures were made at a distance of 60 cm.

At first highly sensitive reversal color film and infrared color film were used for the test pictures, later reversal film with its spectral sensitivity set for artificial light was also used.

3.2 Description of the Photographs on Daylight Reversal Film

For better understanding, Fig. 4 shows the flame structures as derived from analysis of the photograph. First a series of pictures is made without filter. The best one of this series is shown in Fig. 5. The color of the pilot flame was perceived by the eye as blue as its exit from the experimental object changed about 2 cm later into yellow, then to orange and adopted a weak reddish-violet hue in returning to the body. The photograph does not come near to reproducing this color structure. The blue color at the exit from the body is reproduced only as a glimmer of light because of underexposure of the picture hue is also blanketed by the igniter. The reddish-violet hue further back, immediately below the body, is also barely definable as a color on the photograph. Only the yellow color from the center part of the flame is reproduced with more or less fidelity while the burning off of the ignition cartridge of its exit from the body, is overexposed.

When taking a series of pictures with edge filter Schott GG 475 (filter edge at 475 nm) the best one had relatively short exposure (1/120 s as contrasted with 1/25 s without filter). A very clear picture of the center part of the flame is received (Fig. 10). It can be observed, for instance, that it is quite sharply limited at first, becoming diffuse towards the rear. Easily recognizable are also the deposits left behind by the ignition on the outer wing. The initial part of the flame is not reproduced at all, nor is its final part. This may be an indication that the predominant color hûe there must be assigned to the violet end of the spectrum and not to the red one.

Pictures taken with the weaker yellow filter GG 420 show the same part of the flame, only the igniter and the front end of the central part are overexposed so that not as many details can be recognized as with the preceding filter.

The blue filter BG23 was applied so that the blue part of the radiation could be captured separately. This is no edge filter but it has a bell-shaped transmission curve (1) with a /12 gentle slope followed by a longer and steeper slope to shorter wave lengths. Its maximum transmission is at 450 nm. On the pictures only the front end of the center part of the flame is shown. This agrees with the observation that this part is reproduced far brighter when yellow filter GG 420 is used, which also transmits part of the blue radiation, then with yellow filter GG 475.

The red part of the flame radiation is included in the infrared color pictures, according to the film's characteristics it will appear green in that case and appear in the same part of the flame that is shown in pictures where a yellow filter is used.

3.3 Description of the Infrared Exposures

More detailed data about characteristics and use of this film material can be found in [2] and [3], curves of spectral sensitivity and examples for infrared color exposures also in [4].

According to recommendation by the manufacturers, the pictures were taken first with a yellow filter, GG 475 and an orange filter, OG 530. The flame is reproduced essentially white for both filters, without there being a possibility of distinguishing individual flame zones.

For that reason three more picture series were taken with orange filters OG 550, OG 570 and OG 590 (the number shows the location of the filter edge each time). The optimum in color differentiation was here achieved with filter OG 570 (Fig. 11). The injection zone is shown here as white but no details can be recognized in it. It can be seen more clearly when the location of the filter edge is at 590 nm but in that case details are lost all over the rest of the picture.

The infrared photographs also show the rear end of the flame, which is not reproduced at all by the films sensitive to visible light only. It is still underexposed in Fig. 11. To achieve some improvement here two additional series of exposures with longer exposure times were made. To attenuate the visible light in the injection zone in this case even more severe filters were used with filter edges at 645 and 695 nm. The result was negative. Flame and igniter were immersed in a uniform yellowish red, resp. cherry red, in the pictures. /13
Structures could no longer be recognized at all.

In Fig. 11 one more very interesting detail can be seen. Below and behind the flame particle traces of the igniter can be identified. Their light and that of the flame are reflected from the bottom side of the experimental body. A dark spot can be seen on the picture above the rear infrared flame zone. One possible explanation for it is that the light from the igniter does not pass through this part of the flame but is absorbed by it.

3.4 Description of Exposures Taken on Artificial Light Reversal Film

When taking pictures with daylight film the blue radiation contained in the flame does not show up well compared to the brighter long wave radiation. To alleviate this reversal color film was used experimentally, adjusted to a color temperature of 3200 K (tungsten photolamps) in its spectral sensitivity and for that reason relatively more sensitive to blue light than daylight film. Pictures were taken without filter, with a UV-filter UG 2 (for the transmission curve see [1]), with blue filter BG 23 and with yellow filter GG 420.

Pictures taken with the UV-filter were underexposed just like those on daylight film, so much so that even an increase of exposure times, which experimental conditions may just about have permitted, would not have provided sufficient improvement.

Pictures taken with the blue filter differ in their characteristics from the same ones taken on daylight film. In those pictures taken on artificial light film a tongue extends from the flame zone, depicted by itself here, further back and appears larger or smaller according to the exposure time. Its image is so weak, however, that it does not show in the reenlargement of the diapositive (Fig. 8).

Without use of a filter the best pictures were taken during exposure times of 1/250 s, as compared to 1/25 s with daylight film. Because of the short exposure time not only the flame contours become sharper, the picture also experiences less disturbance by the igniter since fewer solid profiles from the /14
ignition cartridge will pass through the picture in the short time (Fig. 6).

In the exposures through the yellow filter GG 420 (Fig. 7) the central part of the flame is shown brown and appears dark at the top near the contour of the experimental body. For pictures without this filter (Fig. 6) this part is consistently brighter. It is brown at the lower edge and violet at the upper one. In the middle it is whitish-grey. This color hue can be explained as a mixture of brown and violet. The brown hue corresponds to orange in the unfiltered picture on daylight film. One may say that there are two flame zones superposed in the central part of the flame with radiation from one being violet and orange from the other.

Fig. 9 shows the reenlargement of a picture, which was taken after the flame had changed considerably because of reconfiguration of the experimental body. After the reconfiguration considerably more fuel was put through. During that experiment acetaldehyde was injected in addition to the fuel. The flame was significantly smaller than before. It is shown blue on the picture, red on a simultaneously made exposure on infrared film. This suggests selective radiation in blue and infrared. Fig. 9, or at any rate the diapositive on which it is based, shows several interesting details. A burning layer of gas can be identified above the depositions left on the outer wing by the igniter. The light traces of solid particles from the igniter are also accompanied by a diffuse light zone. The explanation offered for it is that solid particles, which were supposed to have ignited the fuel/air mixture present, ignite only their own boundary layer and that the combustion does not spread beyond the boundary layer. The light zone around the particle traces is, therefore, the image of the burning boundary layer.

5.5 Analysis of the Flame Structure from the Pictures

According to analysis of the pictures the flame can definitely be separated into individual zones (Table 1):

1. Injection Zone. The pilot fuel, the combustion of the /15
ignition cartridge and air, which is drawn in from outside through the supporting arm, meet in a small chamber inside the experimental body and enter the flow through a joint opening. The first 1-2 cm below this injection opening are considered the injection zone. Here is where a weak blue radiation was observed during the test for which the picture of Fig. 3 was taken. On the photograph the radiation appears so weak that its color can no longer be determined. If an attempt is made to provide some balance through generous exposure then this

zone is submerged by the radiation of the following zone. Color filters are of little use since the following zone is not only brighter generally but also radiates even more blue light. Also submerged by radiation is the injection zone on the infrared photographs (Fig. 11) and also because the light emitted by the following, very bright, flame zone is strongly reflected from the surface of the experimental body. No statement can be made, therefore, whether infrared radiation is present in the injection zone.

2. Main Reaction Zone. Very intensive radiation, which is present in the entire observed part of the spectrum from ultraviolet to infrared (Figs. 5, 6, 7, 8, 10 and 11), starts at a clearly identifiable, fixed, distance from the injection opening. It is to be assumed that an exothermic reaction takes place here, which is corrected with a significant increase in temperature. The flame zone has the shape of a short cone bent backwards. In the previous sections it was always designated as front end of the center part of the flame.

3. Postreaction Zone. After the first intensive reaction has tapered off, enough heat of reaction is still delivered over a somewhat longer path to maintain relatively balanced radiation. This extends from green to infrared (Figs. 5, 6, 7, 9 and 11). In the core of this flame zone there is still some weak blue radiation present (Fig. 8). Attention is also drawn to a system of bright-dark zones, which can probably be explained by compression shocks (Figs. 5, 7, Fig. 6 somewhat less).

4. Luminous Boundary Layer. At the spot where the pilot flame approaches the experimental body again and meets with the boundary layer, violet radiation is present, as can be observed

by a comparison of Figs. 6 and 7. The pilot flame seems to heat the boundary layer here just enough so as to excite selective radiation. /16

5. "Pear." A pear-shaped area is attached to the post-reaction zone, which can only be seen on infrared photographs (Fig. 11). Some infrared light is radiated here and, apparently, visible light and infrared light is absorbed (see section 3.3). This type of radiation suggests the conclusion that it is not due to a significantly high temperature.

6. Boundary Layer of Ignition Particles. A blue zone around the particle traces of the igniter can be identified when the pilot flame is only weakly developed and does not submerge its environment with its radiation (Fig. 9). This is presumably the image of a burning gas layer around the particles.

Cold Pilot Flame. The pilot flame, as shown in Fig. 9, has only selective blue and red radiation. The picture was taken after the fuel consumption was greatly increased through redesign of the model.

3.6 Conclusions

These experimental pictures have produced two types of results: one with regard to the flame itself, the other with regard to the method of multispectral photography.

Multispectral photography has shown itself to be a valuable aid in making a flame structure visible and analyzing it, since quite diverse information is provided about the flame structure, depending on the spectral region in which it is photographed.

The most important information is provided by pictures taken on artifical light film and by infrared photographs. This combination is recommended as standard equipment for the two cameras, since space limitation anyway hardly permits the simultaneous use of more than two cameras. If a third one is somehow accommodated it would be appropriate to use artificial light film in it and an edge filter that cuts off the violet part of the spectrum. The additional information provides a comparison with pictures taken on artifical light film without filter. This recommendation cannot be generalized for all flames and hot gas jets,as is shown in the following example. For that reason test pictures are needed for another experimental arrangement. /17

4. Hot Gas Jet (4500 K) with Compression Shocks

4.1 Experimental Arrangement

Quite different conditions obtained for the second experimental arrangement during which test pictures were taken, than for the first one. Involved was an air plasma jet of about 4500 K, which was generated by means of a rotating arc light. The arrangement was used for determining temperature by means of spectroscopy [6]. Within the service life of the electrodes the flow conditions could be considered approximately stationary. Several cameras were not needed, therefore, since the necessary pictures could be taken, one after the other, with one camera alone. This has the advantage that the exposures were all taken from the same position and through the same optics. The flow condition is not so stationary, however, that individual pictures could be superposed for evaluation.

Because of electrode burning the plasma still contains copper and chromium particles. A nozzle with supercritical pressure ratio and a diameter of 1 cm was used for the pictures.

The equipment for heating the arc light is shown in Fig. 17. Barium Chloride in an aqueous solution was injected to get better results in photographing the jet. Without this injection only the inner core of the jet with the six compression shocks is clearly identifiable.

4.2 Test Pictures of the Hot Gas Jet

Since it is difficult to photograph the jet in the visible part of the spectrum, infrared color film was used exclusively for the test pictures. Test exposures were made with six different edge filters whose edges were at 550, 570, 590, 610, 645 and 715 nm. The result was somewhat surprising.

For exposure with the edge filter OG 570 the jet appears white with a blue-green border but without any other visible structure (Fig. 13).

The picture taken with filter OG 550 appears essentially /18
the same way; only the color hue inside the border is shifted more into the blue.

The structure of the jet is clearly identifiable in the picture with filters OG 590 (Fig. 12) and RG 610 (Fig. 14). For different exposures certain differences resulted in the reproduction of the cone-shaped core zone. With filter RG 610 the outer border of the cone disappears for shorter exposure; with filter OG 590 the compression shocks blend into one another for longer exposures and the core zone is finally shown as homogeneous cone. Fig. 12, in which that is the case, is the reenlargement of a diapositive in which the compression shocks are still individually identifiable.

When taking a picture of the jet through filter RG 645, however, the core structure and the outer border are not shown at all any more (Fig. 15). The jet appears monochromatic yellow. When using filter RG 715, which passes only infrared light, the jet is shown cherry red (Fig. 16).

4.3 Picture Interpretation

Three separate parts can be distinguished in this hot gas jet; the core with the shocks, the outer part of the jet and the boundary region. The core structure is only visible on the pictures that were taken with filter OG 590 (Fig. 12) and RG 610 (Fig. 14). This means that the radiation responsible for the pictures lies between 590 and 645 nm. In the 550 to 590 nm range (Fig. 13) it is blanketed by the copper radiation. That does not necessarily mean that the core has no radiation here. Beyond 645 nm the entire core structure has disappeared. Here it either no longer radiates or its radiation is too weak to be recorded. When photographed on regular color film and viewed with the naked eye, it appears blueish-white to violet. Accordingly, the largest part of this radiation can be found at the short wave end of the visible spectrum. The outer part of the jet can be seen by itself on Figs. 15 and 16. Since it changes its color hue considerably between Figs. 16 and 15, it can be stated that the radiation captured here is distributed in the regions from 645 to 715 nm and from 715 to 990 nm. Another change occurs only between 590 and 570 nm (Fig. 13), representing a further part of the radiation. These are probably the two spectral lines of copper at 578.2 and 579.0 nm.

The third part of the jet is the boundary zone, which is shown in the same way in Figs. 12, 13 and 14,and has disappeared in Fig. 15. One may conclude from this that it radiates between 610 and 645 nm in the red part of the spectrum.

Table 2 summarizes the result. These pictures contained the most important information from the visible part of the spectrum, though the structure of the jet is not recognizable with the naked eye. This contrast probably rests on an optical illusion and the explanation may be that the radiation of the compression shocks is so bright that the rest of the jet falls back compared with it.

5. Hot Gas Jet (25,000 K) /19

The final series of trial pictures was taken of a plasma burner where a hot air jet of 22,000 to 28,000 K is generated (Figs. 18 and 19) by means of an air stream incident longitudinally on a rotating arc light. The jet spectrum consists of a continuum with its maximum in the green part of the spectrum and a superposed line radiation. The jet has a very turbulent outer layer consisting of air, which it pulls along from the periphery. The maximum of the outer layer continuum is located more in the red and infrared regions because of the lower temperatures.

By means of multispectral photography it is only possible to take seperate pictures of the hot gas jet and its outer layer. No statement is obtainable about the inner jet structure.

The hot gas jet itself is reproduced in the pictures on artificial light color film and on those with blue and ultraviolet filters. With increasing distance from the jet nozzle a strong decrease in brightness is recorded. The explanation given is that the line radiation of the jet decreases faster than that of the simultaneously operating continuum, when the jet cools off. This brightness gradation can just about be recorded on reversal film but it is not possible to transfer it to paper prints. The best picture of the outer layer is obtained with infrared color film and a sharp-edged filter with an edge at 590 nm.

For this experimental setup multispectral photography only /20
confirms what is already known from spectroscopy; on the other hand, taking the pictures requires a big effort since the jet is very difficult to photograph for various reasons. For one thing the high contrast in brightness between individual parts of the jet contributes to it. For extended exposure times the contours of the jet appear so smudged that its structure is hardly recognizable any longer. But if a short exposure time is chosen (1/500-1/1000 s) a very disturbing effect occurs. It originates from the fact that due to the high flow velocity (about 1000 m/s) the light trace of a radiating volume element is recorded only partially on the film when the direction of motion of the focal plane shutter is parallel to that of the gas jet. This is the reason why the infrared photographs are not fit for printing.

When applied for plasma jets of this type, multispectral photography requires great effort for a few useable pictures which supply little information.

6. Summary

In view of the fact that conditions for optical flame diagnostics during experiments with supersonic combustion in wind tunnels are highly unfavorable, a method is sought which will provide information about what goes on in the wind tunnel despite the short duration of the experiment and the low luminosity of the combustion phenomena. Multispectral photography, a method applied in aerial reconnaissance and in agriculture, was borrowed from aerial photography and adapted to wind tunnel conditions.

The best results in aerial photography are achieved by making separate exposures for the various spectral ranges on black and white film and by projecting them with the use of multicolored filters superposed upon each other. This presupposes that individual pictures are as nearly identical as possible with regard to the picture frame, exposure angle and time of exposure. Flame photos cannot fulfill this condition since they are taken from a very short distance (all pictures in this report were taken from a distance of less than 1 m). This always creates a very large parallax between individual pictures. It follows that for flame photographs one needs to utilize the extra bit of information in each individual picture, which is offered by color film. During the supersonic combustion experiments the best combination was found to be infrared color film and artificial light color film with special sensitivity to the blue part of the spectrum, with two cameras being used. During evaluation comparison was always made between two simultaneously taken pictures.

An entirely different method of operation was found appropriate for the hot gas jet of 4500 K, which was examined for comparison. In this case the flow pattern could be considered stationary over a long period. Only infrared film was used since the jet was barely visible with the naked eye. In this case various sharp-edged filters were used with the filter edges being 20-25 nm apart. In this way information is gained about the jet structure, and also to which region of the spectrum the radiation from the separate components of the jet belongs.

Although the jet is easy to analyze spectroscopically, the light gain during supersonic combustion is not sufficient for spectroscopic flame diagnostics. The plasma jet of 25,000 K examined last, represents the opposite extreme. It is easily analyzed spectroscopically but difficult to photograph because of its brightness and the high contrasts between light and shadow. The few photographs that do not suffer from faulty exposure also supply very little information.

In conclusion it can be stated that multispectral photography may be employed as a useful aid in the evaluation of combustion experiments. No generally valid method can be recommended, however, for different experimental conditions. Conditions of operation must be adapted individually for each experimental setup.

Dip. Ing. Gisela Stoffers
33 Braunschweig, Bienroder Weg 53

7. References /22

[1] Farb- und Filterglas für Wissenschaft und Technik (Colored and filter glass for science and technology). Jenaer Glaswerk Schott & Gen., Mainz 365/1d. 1962.

[2] FRITZ, L. Norman — Optimum Methods for Using Infrared Sensitive Color Film.
Photogrammetic Engineering 33, 1128-1138 (1967).

[3] PEASE, Robert W. BOWDEN, Leonhard W. — Making Color Infrared Film more Effective High Altitude Sensor.
California Univ., Riverside, Aug. 1968, STAR Accession Number N70-14083, ZLDI-Nr. 0518-2/70.

[4] SMITH, John T. ANSON, Abraham, eds. — Manual of Color Aerial Photography.
American Society of Photogrammetry, 1968.

[5] LUTZ, O.; RIESTER, E. — Überlegungen und bisherige Erfahrungen beim Bau des Heißwasserkanals der DFL in Braunschweig (Considerations on and experiences up to the present in construction of the hot water channel of the DFL in Bruswick).
DFL-Report Nr. 149, Braunschweig 1961.

[6] NEUBAUER, R. F.; ANDERS, K. P.; MODJALLAL, H.; SPIEGEL, K.-H. — Spektroskopische Temperaturbestimmung in einem Heißgas-Freistrahl (Spectroscopic determination of temperature in a hot gas).
DLR-FB 71-75, 1971.

[7] NITSCH, P.; RIESTER, E.; SCHMIDT, N. — Studie über eine Höchstgeschwindigkeitsversuchsanlage für Wiedereintrittsuntersuchungen (Study about an experimental installation for maximum velocities in reentry investigations).
DLR-Mitt. 67-11, 1967.

[8] YOST, Edward F.; WENDEROTH, Sondra — Multispectral Color Aerial Photography.
Photogrammetic Engineering 33, 1020-1033 (1967).

[9] YOST, Edward F. — Multispectral Viewers.
Long Island Univ., Greenvale, N.Y., in: NASA Manned Spacecraft Center 2nd Ann. Earth Resources Program Status Rev., Vol. 2, 1969, STAR Accession Number N71-11988.

[10] YOST, Edward F.; WENDEROTH, Sondra — Agricultural and Oceanographic Applications of Multispectral Color Photography
Long Island Univ., Greenvale, N.Y. /23
in: International Symposium on Remote Sensing of Environment, 6th, Ann Arbor, Mich., October 13-16, 1969, Proceedings Vol. 1, p. 145-173, Ann Arbor, Mich., Michigan, Univ. 1969.

[11] LOWMAN, Paul D., Jr. — Apollo 9 Multispectral Photography: Geologic Analysis.
NASA-TM-X-63714, Sept. 1969.

[12] COLWELL, Robert N.; LENT, Jerry D. — The Inventory of Earth Resources on Enhanced Multiband Space Photography.

California, Univ., Berkeley, Calif., in: International Symposium on Remote Sensing of Environment, 6th, Ann Arbor, Mich., October 13-16, 1969, Proceedings Vol. 1, p. 133-143, Ann Arbor, Mich., Michigan, Univ. 1969, IAA Accession Number A70-26936.

[13] TANGUAY, Marc G. (Ecole Polytechnique, Montreal, Can.); HOFFER, Roger M.; MILES, Robert D. (Purdue Univ., Lafayette, Ind.) — Multispectral Imagery and Automatic Classification of Spectral Response for Detailed Engineering Soils Mapping.

In: International Symposium on Remote Sensing of Environment, 6th, Ann Arbor, Mich., October 13-16, 1969, Proceedings Vol. 1, p. 33-63, Ann Arbor, Mich., Michigan, Univ., 1969, IAA Accession Number A70-26932.

Technical Data Relating to the Photographs /24

Fig. 5:	Kodak Ektachrome High Speed Film (Daylight) f:2 1/25 s Enlargement via black and white negative.
Figs. 6-9:	Kodak Ektachrome High Speed Film (Tungsten 3200 K)
Fig. 6:	f:2 1/250 s.
Fig. 7:	Schott filter GG 420, f:2 1/100 s
Fig. 8:	Schott filter BG 23 f:2 1/250 s
Fig. 9:	f:2, 1/250 s.
Fig. 10	Kodak Ektachrome High Speed Film (Daylight) Schott filter GG 475, f:2 1/100 s.
Fig. 11:	Schott filter OG 570, f:2.4, 1/25 s.
Fig. 12:	Schott filter OG 590, f:3.3, 1/25 s.
Fig. 13:	Schott filter OG 570, f:2.8, 1/25 s.
Fig. 14:	Schott filter RG 610 f:2.4, 1/25 s.

Fig. 15:	Schott filter RG 645 f:2.4, 1/25 s.
Fig. 16:	Schott filter RG 715 f:2.8, 1/25 s.
Fig. 17:	Agfactor-negative film, color enlargement.
Figs. 18 and 19:	Extended Range (XR) Film (Applied Photo Sciences, Inc., 388 Hillside Avenue, Needham Heights, Mass., 02194, USA).
Fig. 18:	f:3.3, 1/250 s developed as color negative film, black and white enlargement.
Fig. 19:	f:4, 1/250 s developed per Kodak process C-22 as color negative film. Enlargement via black and white--positive and negative.

Note /25

Considerable loss of picture quality occurred in nearly all photographs during transposition from diapositives to paper positives, the exception being a few of the infrared photographs. For that reason the details, which are mentioned in the text and part of which is very important, are not always recognizable. Still, the use of reversal film is recommended for two reasons. Color diapositives have a much greater range of contrast than paper positives, which is important for flame photographs. In addition uncontrollable color shifts due to filtering in the laboratory occur during enlargement of color negatives. It is true that one knows the film material and the transmission curves of the filters that one has used. But since it is not known which filters the color laboratory doing the film processing is using and what their properties are, it is not possible to consider this influence correctly in the evaluation and interpretation of the pictures.

TABLE 1 /26

SUMMARY OF RESULTS FROM PHOTOGRAPHS OF SUPERSONIC COMBUSTION

Injection Zone	Visually Observed			
Main Reaction Zone	X	X	X	X
Postreaction Zone		X	X	X
Luminous Boundary Layer	420 nm			
"Pear"			Absorption?	X Absorption?
Boundary Layer of Particles	X			?
Cold Pilot Flame	X			X
	blue	green	red	Infra-red

TABLE 2

SUMMARY OF RESULTS FROM PHOTOGRAPHS OF THE HOT GAS JET WITH COMPRESSION SHOCKS

Core and Compression Schocks		?	X	X		
Outer Part of Flame	?	X			X	X
Marginal Zone	X			X		

Filter Edges: 550 570 610 645 715 nm

(X=radiation present)

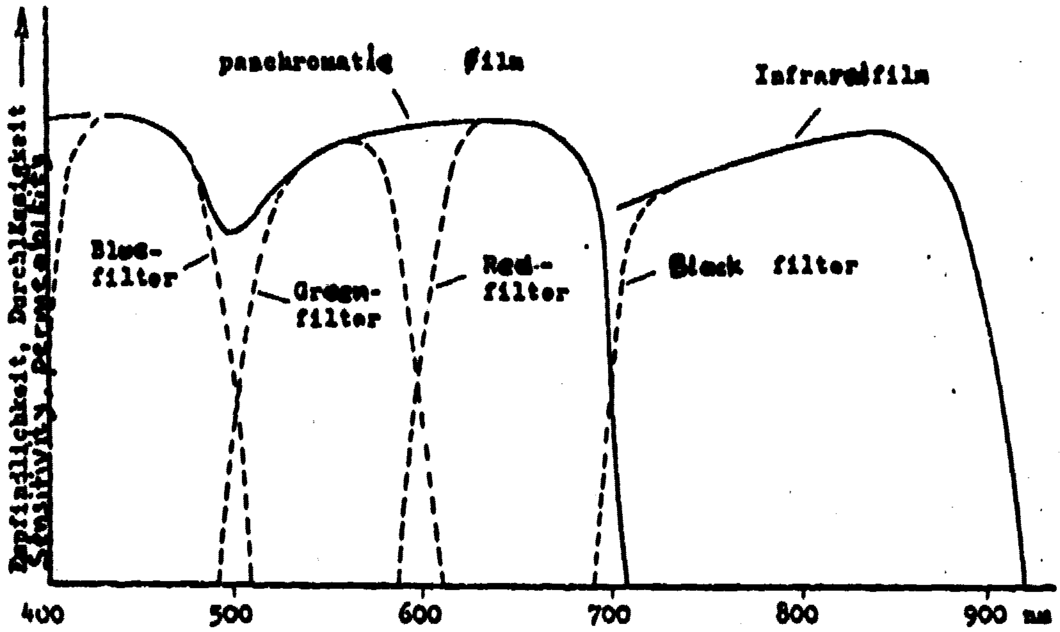

Fig. 1. Multispectral photography with four cameras.

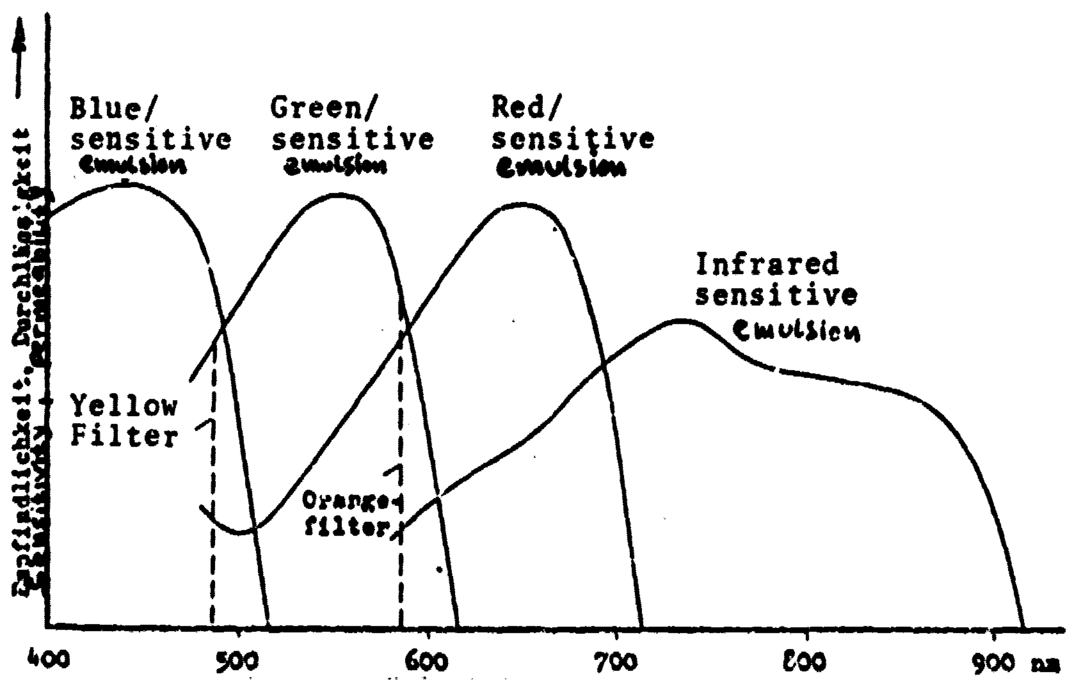

Fig. 2. Sensitivity curves of color films.

/28

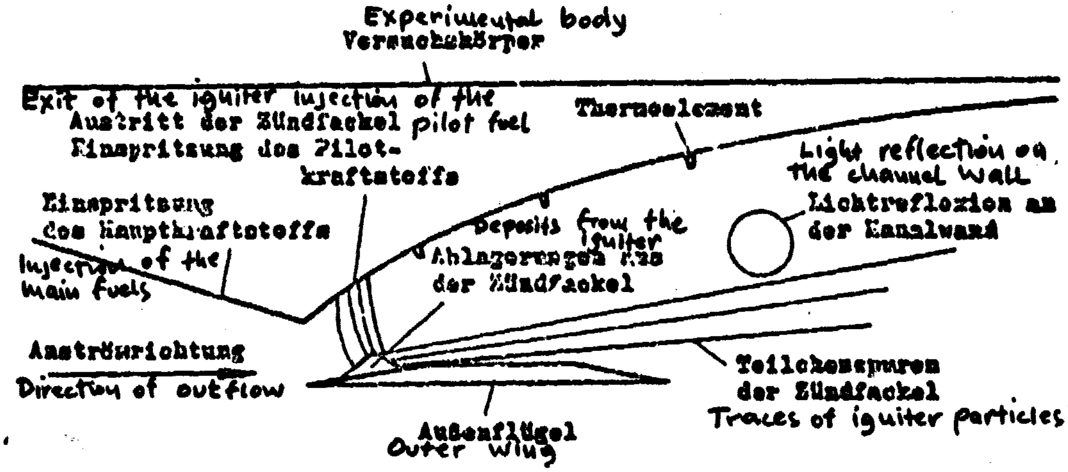

Fig. 3. Supersonic combustion. Experimental arrangement.

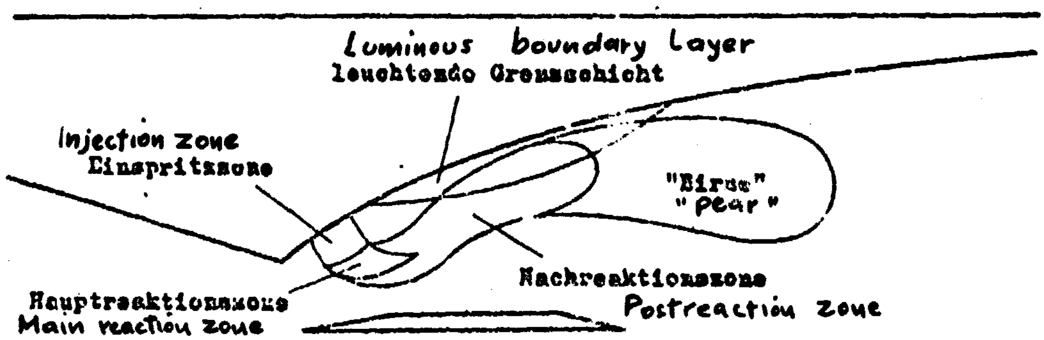

Fig. 4. Supersonic combustion. Flow pattern of pilot flame.

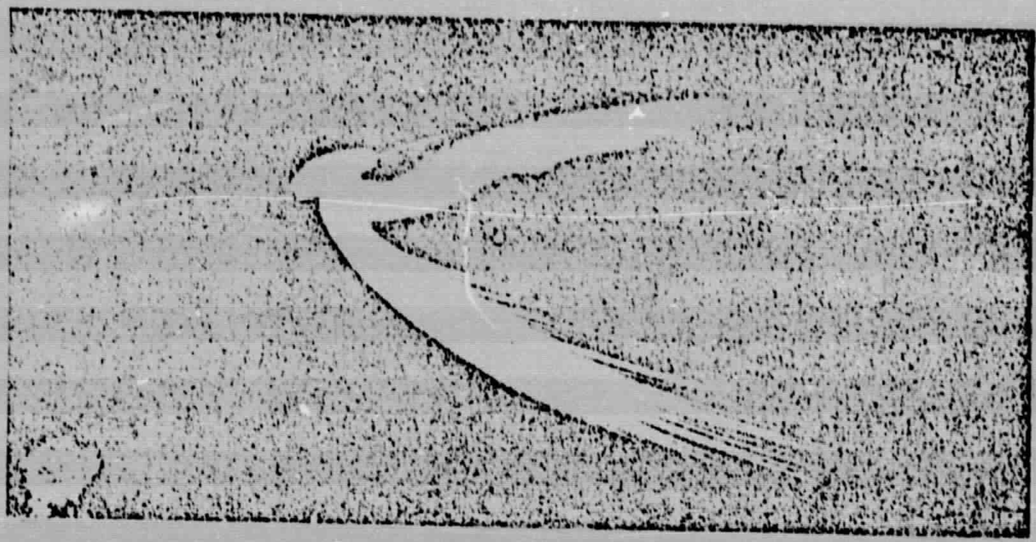

Fig. 5. Supersonic combustion. Experimental arrangement without outer wings. Daylight film without filter.

Fig. 6. Supersonic combustion. Artificial light film without filter.

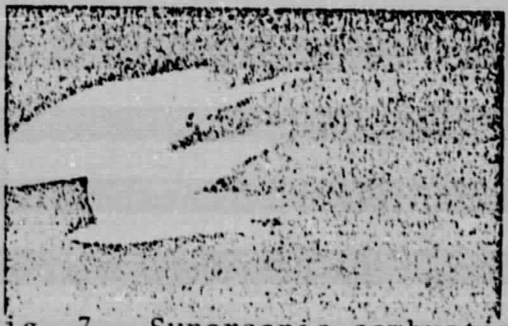

Fig. 7. Supersonic combustion. Artificial light film with bright yellow filter.

Fig. 8. Supersonic combustion. Artificial light film with blue filter.

Fig. 9. Supersonic combustion. Cold pilot flame. Artificial light film without filter.

/30

Fig. 10. Supersonic combustion. Daylight film with yellow filter.

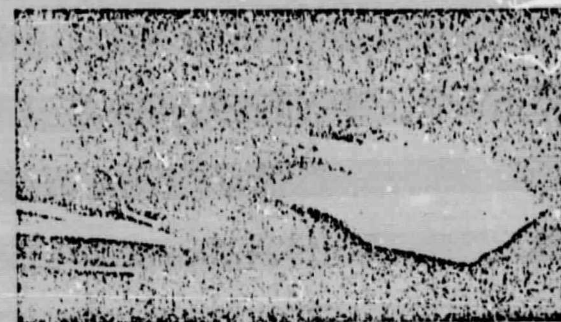

Fig. 11. Supersonic combustion. Infrared picture.

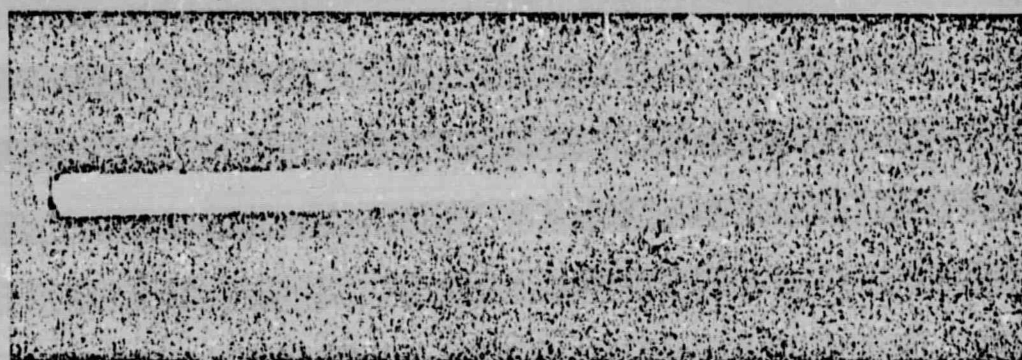

Fig. 12. Hot gas jet (4500 K). Infrared pictures. Filter edge at 590 nm.

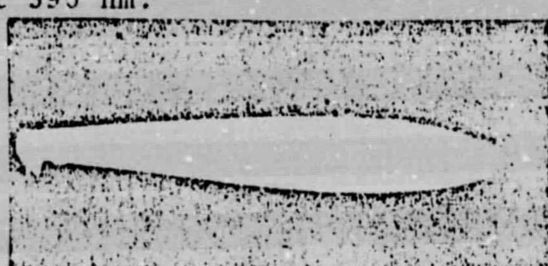

Fig. 13. Hot gas jet (4500 K). Infrared picture. Filter edge at 570 nm.

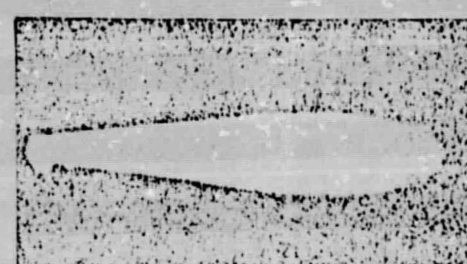

Fig. 15. Hot gas jet (4500 K). Infrared picture. Filter edge at 645 nm.

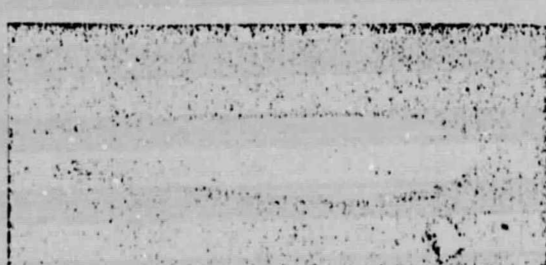

Fig. 14. Hot gas jet (4500 K). Infrared picture. Filter edge at 610 nm.

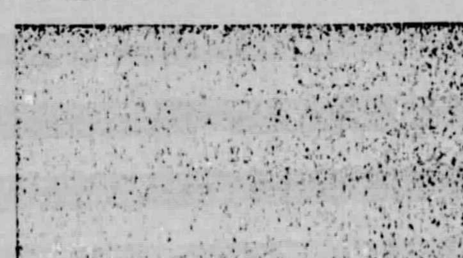

Fig. 16. Hot gas jet (4500 K). Infrared picture. Filter edge at 715 nm.

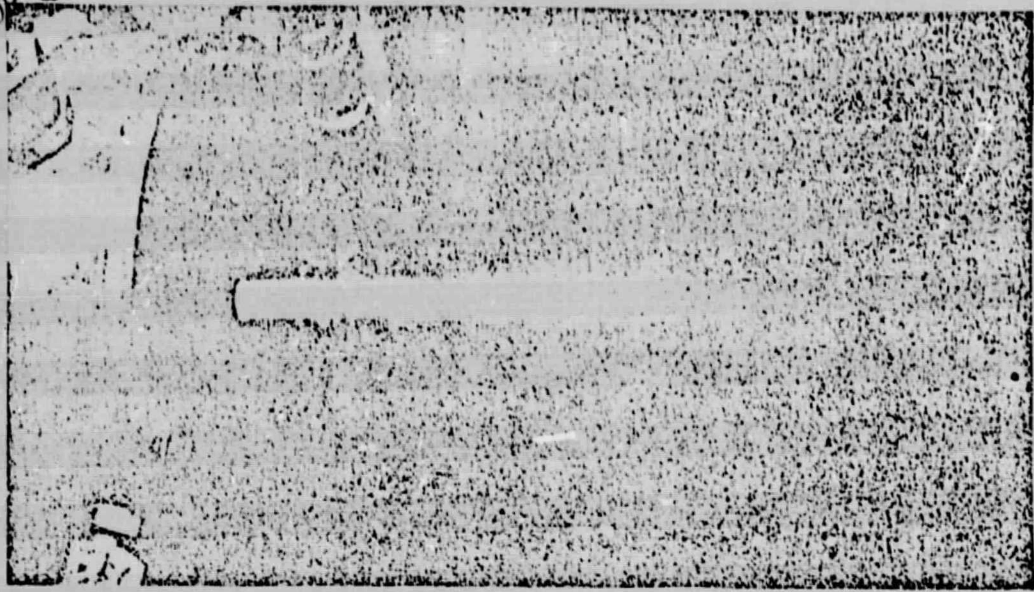

Fig. 17. Hot gas jet (4500 K). Experimental arrangement.

Fig. 18. Hot gas jet (25,000 K).

Fig. 19. Hot gas jet (25,000 K).