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THEORETICAL AND EXPERIMENTAL STUDY OF INFRARED RADIATION FROM HELICOPTERS

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1.0 INTRODUCTION

Missiles that home on infrared radiation represent an increasing threat to helicopters, just as they are for airplanes. It is therefore necessary to reduce the infrared emission of these aircraft. The first practical step, based on the knowledge of the heat-emitting points of airplanes, consisted in placing masks to reduce the radiation signature emitted by the helicopter. Substantial gains were rapidly achieved with this method. However, given the development of seekers it has become necessary to search for other signature-reducing methods.

Only a methodic approach to the problem will allow more efficient camouflage. Details of a study program has been settled by SNIAS and ONERA. It comprises theoretical assessments and measurements - i.e. two procedures that are self-supplementing.

During the first phase where a working tool had to be developed, the studies carried out dealt with existing helicopters. Subsequently, it will be necessary to use this tool to study methods of signature reduction and to determine the progress achieved.

The study explained in this paper deals with infrared radiation from the helicopter jet. The first section describes the theoretical efforts made essentially by Aerospatiale. These experimental studies are necessary for fine-tuning the development of jet radiation modelization programs. Tests are performed at the Aerospatiale rotor test rig. They are run on a jet at turboshaft-engine outlet. Two types of test data are obtained:

- Measurement of temperature and pressure in the jet. This allows us to know the aerodynamic and thermodynamic parameters at system outlet and to obtain the aerothermic chart of the jet.

- Measurement of the jet IR-emission. This is the most important part of the experiment and only it will be covered by the rest of this paper.

2.0 THE CRIRA PROGRAM

At the request of STTE, an aircraft infrared radiation computation code was developed at ONERA, a few years ago. The program was called CRIRA (Calcul du Rayonnement Infrarouge des Avions). It is fairly extensive and covers all aspects of the problem. Figure 1 illustrates the general program organization.

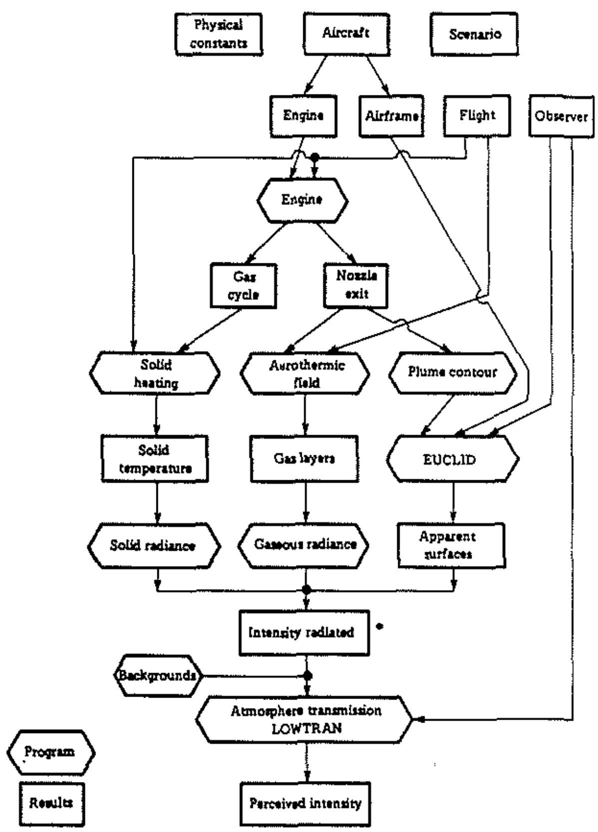

Figure 1

The basic data is divided into three groups. The first is general and does not cover the precise calculation mentioned. It relates, for example, to the average composition of the atmosphere or to the radiation properties of gases. Data of the second type details the overall experimental factors - geometry and power plant of the aircraft, photometric properties of surfaces and observation facilities used, spectral band and distance of observation. The third group of data sets the precise conditions of simulation and is essentially related to flight - engine rating altitude, speed of aircraft, aspect angle of aircraft.

The calculation itself starts by an assessment of the thermal effects that appear on the surface of the aircraft and in the jet because the temperature field plays a fundamental part in infrared emission.

Firstly, the basic engine operating characteristics are reconstructed to allow for the engine used and the circumstances of the fligt at the time of modeling. The calculations are designed to estimate the temperatures of the various parts that are more or less easily visible from the outside. They also give the parameters of the gases at nozzle exit.

Another section of the calculations, based cn this data, determines the features of the jet, that is, the aerothermic field with details of the trail of gases that follow the aircraft during flight. The calculation is limited to the space in which the temperature of the molecules present is sufficiently high to contribute significantly to the infrared radiation of the whole. Concentration of active molecules is also estimated during this calculation. Finally, a third section of the program calculates the effects of kinetic heating and attributes a temperature to each section of the airframe surface that is visible from the outside.

Before calculating the radiation emitted, the program determines the surfaces of the aircraft which are seen by the observation system. For this purpose, a description of the aircraft is entered into the computer by means of software Euclid (see ref. 1). This software provides the creation, handling and representation of three-dimensional geometric figures with elimination of the hidden sections. The aircraft and the jet are simulated by a series of flat facets and Euclid determines the apparent areas of the visible facets.

Radiation from solid sections is calculated from the laws of Plank and of Kirchoff. Calculation of infrared emission by gases makes use of more complex techniques which will be explained below.

The atmosphere plays an indirect part in the radiation as an input parameter of calculations relating to the engine, but it plays a more direct role in relation to two points:

-- The radiation emitted by the atmosphere is the background against which the aircraft stands out. Moreover, part of this radiation is reflected on the surfaces of the aircraft and contributes to the observed radiation.

-- The atmosphere attenuates radiation very selectively, depending upon the wavelength of the radiation emitted by the aircraft. The infrared active molecules of the jet, in particular, exist also in the atmosphere and reabsorb part of the radiation emitted.

The problems of atmospheric emission and transmission are processed by programs derived from the Lowtran 4 code.

The whole CRIRA program is more specifically adapted to airplane problems and is therefore not directly applicable to helicopters. Nevertheless, subroutines of general code cover:

-- the aerothermic description of the jet,

-- the calculation of radiation from hot gases,

-- the atmospheric effects,

and can easily be adapted to helicopter jets. They are collected in the form of a self-contained set which provides a basis for calculation.

3.0 THEORETICAL CALCULATION OF INFRARED RADIATION FROM HELICOPTER JETS

3.1 AEROTHERMIC FIELD OF THE PLUME

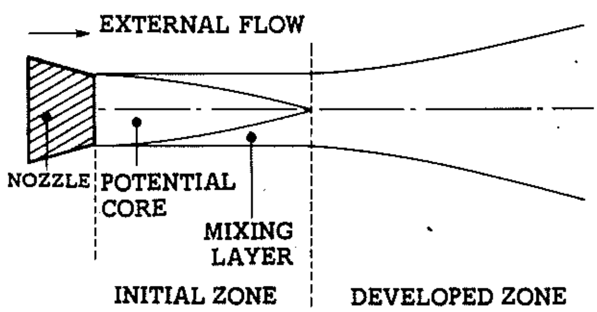

Figure 2

For the purpose of calculations, the aerothermic field of the helicopter jet is divided into two zones (figure 2). The zone immediately behind the nozzle comprises the potential core, where the initial conditions are maintained practically unchanged. This potential core is edged by a turbulent mixing layer which progressively invades the whole jet. The second section of the jet is entirely turbulent, and when the distance is increased from the nozzle outlet, the parameters of the aerothermic field come close to those encountered in the outside air (see figure 3A).

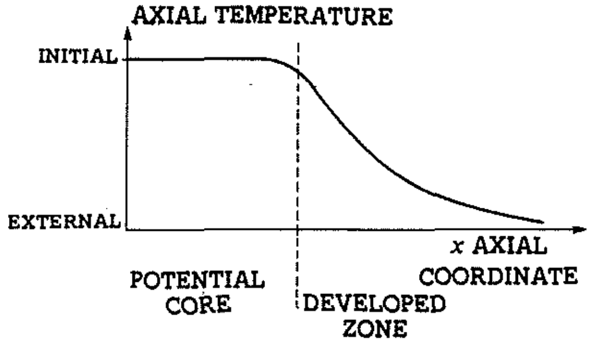

Figure 3A

The transversal profiles of speed, temperature and concentration in the initial zone are of nearly trapezoidal shape. The profiles in the mixed section are almost gaussian (figure 3B). The whole of these transversal profiles can be described by a series of analytic formulas which are deduced from theoretical considerations. The numerical values result from experimental data.

CROSS-SECTIONS

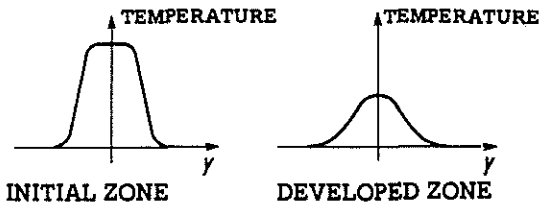

Figure 3B

The main formulas used are indicated below.

The length of the potential core is given by the empirical formula:

$$C = \frac{4\ D\ (1 + \alpha M)}{0.15 + |\ 1 - \lambda|} \sqrt{\frac{Te}{Tj}}$$

D = jet diameter
M = jet Mach number
λ= ratio between speed of external flux and jet speed
α= proportionality coefficient near 1
Te = temperature of external flux
Tj = temperature of jet at nozzle outlet

Decrease of parameters over axis is given by:

$$fa(X) = 1 - \exp \frac{1}{\left(\frac{x}{c}\right)^{p} - a}$$

where a = 0.6, p = 1
X = x/D : reduced variable on the axial coordinate
D = initial diameter of jet

The same transversal function is applied to the two zones of the jet.

$$fr(R) = \frac{1}{2}\left[1 + th\left[\frac{Rm}{\delta}\left(\frac{Rm}{R} - \frac{R}{Rm}\right)\right]\right]$$

In this formula, Rm and δ respectively represent the average radius of jet and thickness of the mixing layer in the form of standardized coordinates. In the initial zone (X < C) and for null outside air speed :

Rm ■ 1

and δ has a linear growth between X = 0 and X = C :

$$\delta = \sqrt{2}\ \frac{X}{C}$$

In the developed zone (X > C) :

$$Rm = \frac{0.89}{fa(X)}$$

$$\delta = \sqrt{2}\ Rm$$

In the case of helicopters, two supplementary phenomena disturb the organization of the aerothermic field.

First, the blast from the rotor curves the end of the jet downwards at the rate at which the blades pass by and increases the turbulence and the speed of the mixing.

Second, the form of the nozzle which is often complex, and allows passage of the engine shaft, destroys the symmetry of revolution of the jet. The analytic formulas, under these conditions, cannot claim to precisely describe the phenomena but can only give a near illustration.

Exact calculation by means of equations relating to fluid mechanics is also very difficult, particularly on account of the lack of precise data on the initial conditions. Consequently, the description given by analytic forms has been maintained with the exception of a few modifications and details.

3.2 RADIATION OF GASES

A helicopter jet basically consists of nitrogen, oxygen, water vapor and carbon dioxide. Among these gases, the molecules of H_2O and CO_2 are the most active in the infrared. In the waveband around 4 microns we are concerned with, the radiation is due to a CO_2 rotation-vibration band covering the spectral range from 4.1 to 4.8 microns. This band is in fact subdivised into several thousands of lines of extremely variable intensity depending on the wavelength and its parameters evolve rapidly with temperature.

Detailed calculation is complex and very long and has not been retained in this study.

Nevertheless in order to cope with the very high temperature gradients and with gas emissivity, we divided the jet spatially into small zones and spectrally into small intervals.

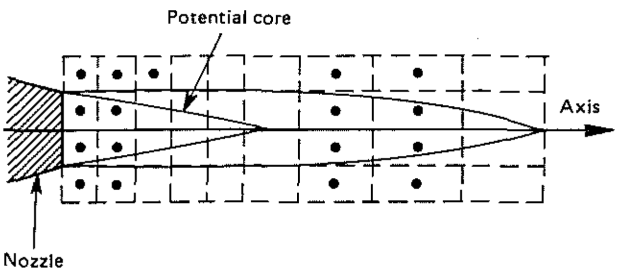

Figure 4

Spatially, the jet is covered with a grid (figure 4). The intensity radiated is the product of radiance calculated at the center of each mesh by the visible area of the mesh. Overall intensity is obtained by totaling the intensities of all the meshes that cover the jet.

Every infrared ray that crosses the jet encounters several layers of gases of variable temperatures and CO2 concentrations. For calculation of radiance, the jet is simulated by a series of gas layers of different temperature and concentration that supply the conditions encountered by a ray crossing the jet. The difference of temperature between the layers of gases is about one tenth of the total difference between the temperature at nozzle outlet and the outside air (figure 5).

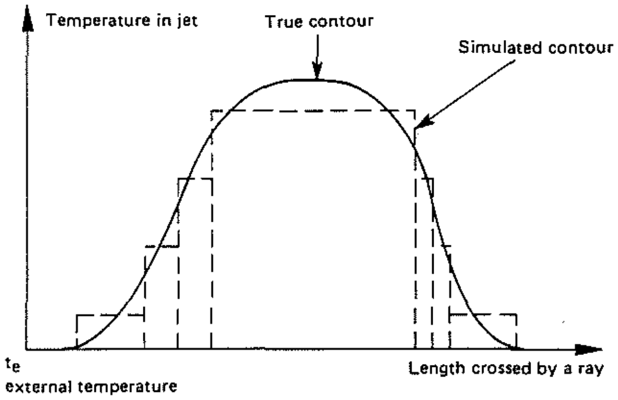

Figure 5

Spectrally, the interval is cut into 50 bands of 5 cm-1. The emission coefficient in each basic interval varies very rapidly with the wavenumber (figure 6). The approximation that consists in illustrating all these coefficients by a single mean value is not sufficient. A much better result is obtained by defining three parameters for each spectral interval. Two of these parameters are associated with the mean value and with the mean quadratic difference of the coefficients. The third is adjusted to allow for the effects of correlation that exist between the layers - for two different temperature layers, the coefficients are fairly close but are not identical. The radiation emitted by an internal layer of the jet is partially reabsorbed and partially completed by the layers outside the jet. Moreover, the air between the jet and the observer also contains CO2 and absorbs a substantial quantity of the emitted radiation. The air is therefore considered an extra layer of gas in all calculations. These calculations are described in greater details under ref. (2).

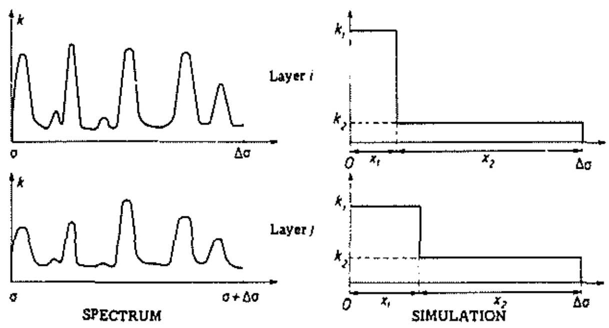

Figure 6

In the spectral band studied, the jet is not entirely opaque. The observer sees the background partially through the jet. Calculation of the luminance seen in a given direction by the observer is therefore performed by using a distant point as a starting point, then adding the contribution of each jet layer and allowing for atmospheric attenuation (figure 7).

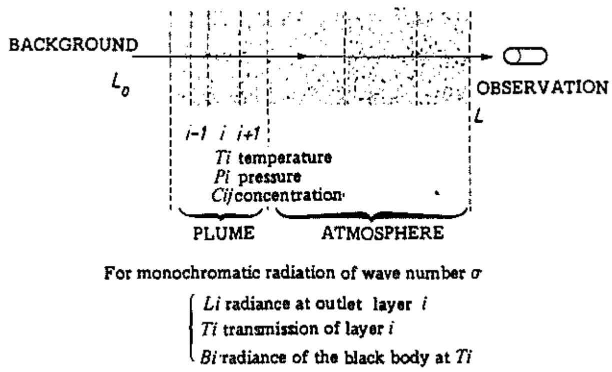

Figure 7

3.3 EXAMPLES OF RESULTS

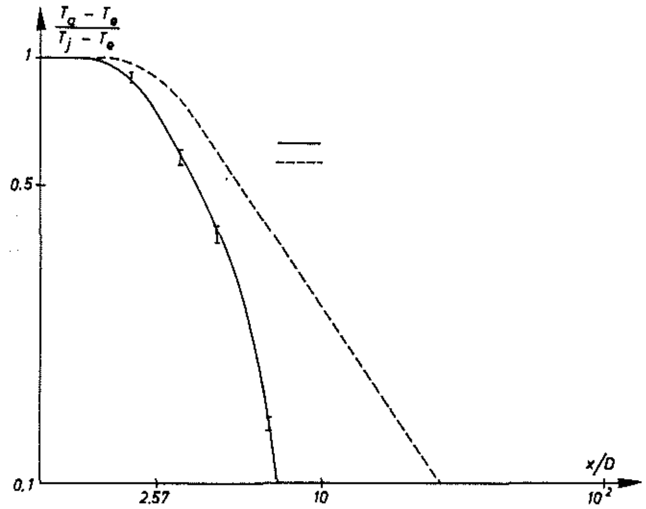

Figure 8

Figure 8 illustrates a standard temperature profile on the jet centerline. The dotted curve illustrates a conventional theoretical profile obtained from coefficients a and p respectively 0.6 and 1. The solid curve illustrates an experimental profile. The difference between these curves is due to the perturbation induced by the rotor blast. A rate of dilution is calculated from these two curves to adjust the theoretical profile and the experimental profile.

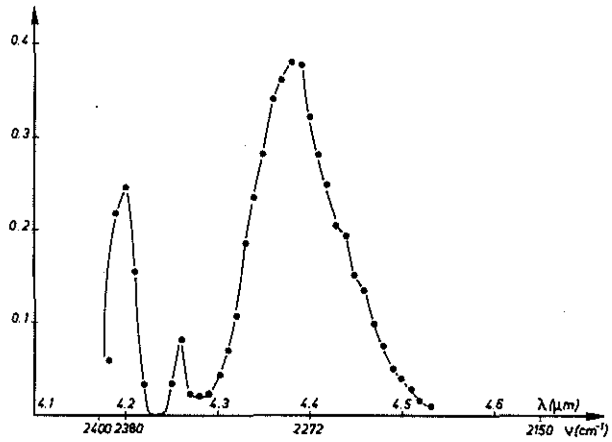

Figure 9

Figure 9 illustrates the spectral signature of the jet as it may be perceived by an instrument placed at a distance of 10 meters and aiming across the jet.

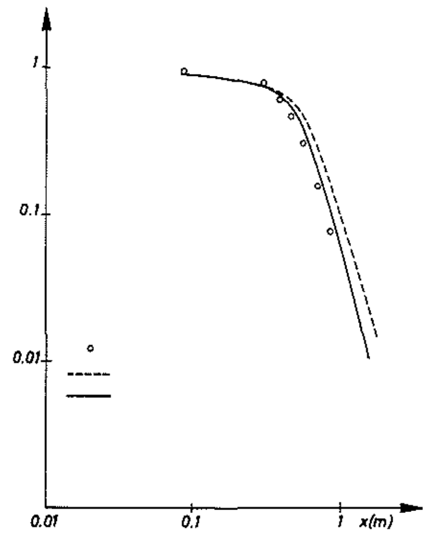

Figure 10

The figures for radiance on the jet centerline are given in figure 10. The dotted line corresponds to a conventional aircraft jet, the solid line to a jet disturbed by the helicopter rotor blast.

4.0 TESTING MEANS

They comprise three main elements:

- The rotor rig,
- The infrared camera,
- The spectrometer.

4.1 ROTOR RIG

The system comprises the engine, the gear box and the rotor. It allows us, within the framework of this study, to look closely at the influence of blade rotation on aerothermic representation and on jet radiation.

It also allows to isolate the engine jet - the very subject of our research - from the infrared emission radiated from the rest of the aircraft.

4.2 TESTING INSTRUMENTS.

We use an AGA model 680 thermal camera fitted with an indium antimonide sensor which allows to work in the 3.3/5.6-micron bandwidth. It is connected to a color video screen and an AMPEX analogic recorder.

We use a CI model SR1000 spectrometer which allows to obtain results in the 2.5/6-micron bandwidth with the filters used. The test data is recorded on an HP-9825 computer. Sighting is done on a 5-milliradian circular field.

5.0 DATA ACQUISITION METHOD.

5.1 CALIBRATION

The data from the spectrometer does not require conversion into physical values. The purpose of calibration is to obtain a continuous relation.

This is due to the fact that the instrument uses two continuous filters forming a ring on a disk driven by a step motor. These filters are sensitive to wave lengths between 2.5 and 4.5 microns for the first filter and between 4.4 and 6 for the second. For both filters, there is a linear relation between the angular position of the filter and wave length transmitted, but there is no continuity between the two relations.

Data processing in that case consists in obtaining a continuous representation of the spectrum between 2.5 and 6 microns by allocating a wave length to each of the steps of the filter-driving motor.

The sensor fitting out the camera is calibrated with a black body for each of the diaphragms used during data acquisition. This calibration makes it possible to obtain the relationship between the black body temperature and the radiant emittance (or radiance) received by the sensor.

To that end, one uses:

- the spectral distribution of the black body radiant emittance given by Planck's law:

- The transfer function of the camera supplied by the manufacturer.

- The emissivity coefficient of the black body.

5.2 EQUIPMENT LAYOUT.

The measuring equipment is placed at the shortest distance possible for recording the entirety of the jet during thermographic data acquisition. The distance selected for all experiments conducted so far is comprised between 7 and 10 meters.

Moreover, instruments are placed in a plane normal to the jet axis. Where the latter is horizontal, one tries to locate them in such a manner that the elevation angle be as small as possible.

Finally, the radiation from the hot metal surfaces at system outlet is basically different from that of the jet. To get rid of it, the hot sections are masked with a container full of water at ambient temperature.

5.3 SPATIAL CALIBRATION

The thermal camera performs a horizontal scanning and the video signal of each line is sampled. The image thus obtained is stored as a matrix every element of which is representative of a radiant emittance (or radiance) received by the sensor and of an elementary surface belonging to the field on which the camera is focused.

It is important to know the area of the elementary surface as the results expected are dependent on the area. Therefore we place an IR-spotlight system in the vertical plane through the jet axis, the relative location of the spotlight being known.
Acquisition with the thermal camera makes it possible to identify the number of elementary samples comprised between two spotlights and hence to deduce the value of the elementary area.

6.0 DATA PROCESSING

6.1 ELIMINATION OF BACKGROUND

In each case, two different types of data acquisitions are performed:

- with the system operative, which makes it possible to "see" the jet,

- with the system inoperative; in that case, only jet-external elements are "visible" and especially the background i.e. a tarpaulin placed behind the jet, or the sky or the more common combination of the two.

In the case of thermographic recording, deducting the values obtained for the two images makes it possible to:

- eliminate the background radiation, i.e. possible variations in its temperature between two consecutive experiments,

- grant less importance to the selection of jet boundaries,

- leave out of the final result the radiation of the background as the jet is essentially a semi-transparent medium.

The radiation measured will therefore be that of the pure jet independently of its environment.

As regards spectrometric measurements, a wave-length by wave-length deduction makes it also possible to obtain the law for spectral distribution in gas by eliminating the amount of radiation generated by the background.

6.2 IMPORTANCE OF SPECTROMETRIC MEASUREMENTS

Figure (11) shows an example of spectral distribution of the radiation in the turboshaft engine jet.

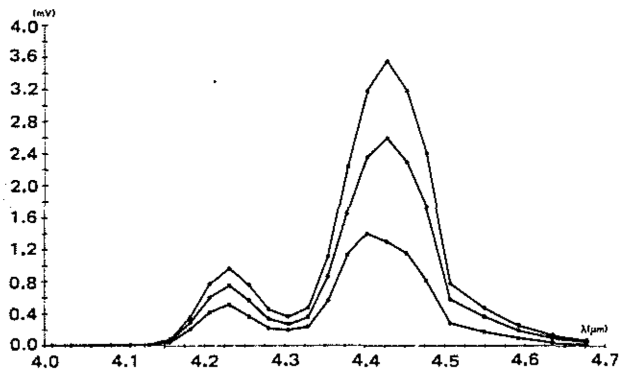

Figure 11

One can see:

- gas radiating in the 4.1 to 4.6-micron band,

- a trough around 4.25/4.30 microns which corresponds to the absorption band of the cold carbon dioxyde contained in atmospheric path between jet and observation.

One sees that the hot gas jet does not radiate in the same manner as a black body. The relations established during calibration are not directly applicable for converting into physical values the results given by the thermal camera.

Therefore, in order to know the radiation of a given point it is necessary to apply:

- the spectral distribution law of jet radiation.

- the camera transfer function.

Once this processing phase has been completed, one knows the value of radiant emittance (or radiance) for each area element.

6.3 JET RADIATION

All subsequent processing is based, as explained previously, on the image representing the jet independent of its environment.

The last processing phase will allow to determine the global jet radiation. One ticklish point remains unsolved though. In fact, the boundary between the jet and the jet pipe metal parts - or the water container used to mask the hot sections - must be determined accurately.
To that end, one plots a certain numberof significant lines representing the jet.

It is then possible on these lines to determine the boundary between the jet and the useless part of the image. This boundary is easy to identify as the lines selected are broken on account of a difference in radiation laws.

Jet boundaries being known, we opt for an iso-level curve representation (see figure 12). We calculate the energetic intensity generated by the area comprised between two consecutive curves in order to quantify the relative size of the various zones. The result is obtained by adding together the energetic intensities from each of the various elementary areas constituting the total zone considered.

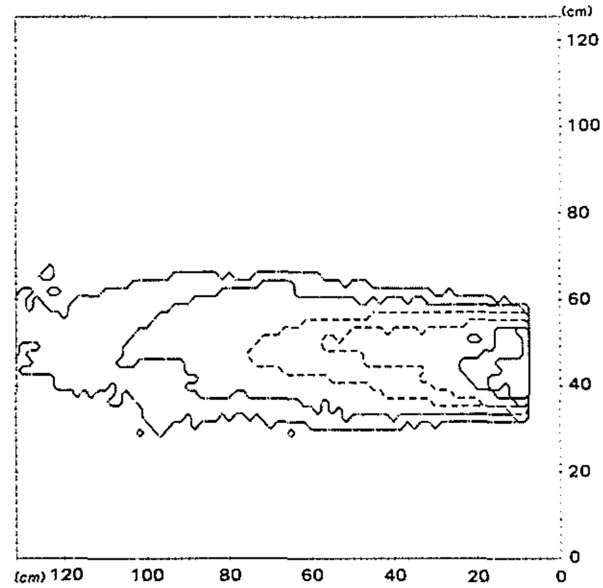

Figure 12

Total jet radiation is represented by the sum of energetic intensities generated by the total zones.

7.0 CONCLUSION

Infrared radiation from helicopter exhaust jets was the subject of a systematic study led jointly by Aerospatiale and ONERA.

On the one hand, the experimental data collected by Aerospatiale in the aerothermic field made it possible to give validity to the proposed theoretical formulas. On the other hand, numerical radiation calculations performed by ONERA were confirmed by infrared measurements made in Marignane on actual jets. Agreement between measurements and calculations is on the order of 90 % for all tests.

The techniques developped, both from a theoretical and an experimental point of view are henceforth applied to the problem of reducing the infrared *signature of exhaust* jets.

Substantial results have already been achieved.

8.0 BIBLIOGRAPHIC REFERENCES

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