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PRELIMINARY INFRARED RADIATION EMISSIONS PROGRAM (PIREP)

Volume I - Description

Aircraft Engine Group
General Electric Company
Cincinnati, Ohio 45215

15 November 1976

FINAL REPORT

Distribution limited to U.S. Government agencies only; report contains test and evaluation information, November 1976. Other requests for this document must be referred to ASD/XRH, Wright-Patterson Air Force Base, Ohio 45433.

Prepared for:
Deputy for Development Planning
Aeronautical Systems Division
Wright-Patterson Air Force Base, Ohio 45433

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The background and development of a computer program, PIREP (Preliminary Infrared Radiation Emissions Program) for rapidly generating engine IR emission characteristics is presented. The PIREP program evaluates peak plume and peak hot parts infrared emissions for turbojet, turbofan and turboshaft engines at low cost to the user. The report presents the analysis and discusses the applications of the program.

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FOREWORD

This report is the product of a jointly planned and corrdinated effort under cognizance of the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), Naval Air Systems Command, Code 5204J, Washington, D. C. 20361. The JTCG/AS is a chartered activity under the aegis of the Joint AMC/NMC/AFLC/JTCG/AS-CM-G-03. This effort was managed by USAF Aeronautical Systems Division, Deputy for Development Planning, ASD/XRHP, S. E. Tate, WPAFB, Ohio 45433.

The development of this program and the preparation of the report was performed by the Aircraft Engine Group of the General Electric Company, Cincinnati, Ohio.

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Terrell E. Horne
TERRELL E. HORNE
Colonel, USAF
Deputy for Development Planning

SUMMARY

A new design tool, the Preliminary Infrared Radiation Emissions Program (PIREP) has been developed to bring the infrared emissions considerations into the realm of configuration definition and preliminary design of aircraft.

This development sponsored by the Air Force has been achieved through the cooperation of USN/ONR code 211 and USAF/ASD/XRH in a series of studies to compile, organize, and manage the existing extensive data base of infrared knowledge and related influences on aeronautical systems survivability.

The initial application of pirep prove it to be very cost effective in preliminary configuration infrared considerations by reducing preliminary IR analyses, in one instance, from $12000 to $10 and analyses schedule time from 130 working days to 15 working days.

The background and development of a computer program, PIREP (Preliminary Infrared Radiation Emissions Program) for rapidly generating engine IR emission characteristics is presented. The PIREP program evaluates peak plume and peak hot parts infrared emissions for turbojet, turbofan and turboshaft engines at low cost to the user. This report presents the analysis and discusses the applications of the program.

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1. INTRODUCTION

Combat aircraft must be able to defy, or at least defer, enemy attack if they intend to successfully deter enemy aggression. Such survivability of a combat aircraft can only be derived by proper design as a target aircraft, implying a low "kill" percentage for the attacker.

Designers of military aircraft recognize that scoring a "kill" occurs in six basic stages.

- "Detection" is necessarily the first stage since a target cannot be fired upon until its presence is known.
- "Acquisition" consists of watching or tracking the target.
- "Convergence" constitutes taking "aim."
- "Firing" the weapon represents the fourth stage.
- A "Miss" will terminate the sequence in stage five, or
- The "End Game" will determine the result of a hit in stage six as a "kill" or "survival."

Military aircraft designers are, in fact, designers of targets. Observability reduction or control must be paramount in order to avoid the "kill" by denying or making difficult the stages of detection, acquisition, convergence and a "hit" if the weapon is a guided missile. Observability concerns radar, optical, infrared, and reflective physics.

The effort reported herein concerns itself with the infrared (IR) observables of aircraft and new methodology specifically tailored to an aircraft design where it can have maximum benefit. Although aircraft planners and designers have been aware of IR emissions and have had access to IR data for many years, methods for applying this knowledge early in the design have never before been available. IR considerations have been forced into a post-design position, an extremely unwieldy and expensive position for it to be as proven by many design histories.

During concept definition (CD) the preliminary design (PD) activity many tens or a few hundred configurations of engine cycles and components as well as airframe components must be tentatively evaluated to evolve a desirable few candidate designs. One of these candidates then becomes designated a baseline for additional design and mission capability comparison. Obviously, many (IR emission) critical decisions have already been made at this stage. If IR emissions are to be successfully managed in aerospace systems design, it must be integrated into the CD and PD activity.

A new data management scheme, developed in this effort, is especially tailored to make IR knowledge available for CD and PD. The Preliminary Infrared Radiation Emissions Program (PIREP), a quick inexpensive computer routine for evaluating IR emissions, was designed to be an attachment for customer engine performance decks to produce IR emission parameters along with all other engine performance parameters. PIREP is suitable, also, for inclusion in engine performance parametric decks, or it can be operated independently for more detailed or parametric studies. PIREP was developed for the U.S. Air Force under contract F33615-76-C-0117.

PIREP was initiated as a result of the IR Handbook program sponsored by the USN, Office of Naval Research (Ref. 1), a program which has concentrated on gathering current methodology, organizing the extensive data base of infrared knowledge, and increasing survivability through improvement of analytical tools.

A technique utilizing data correlation analysis, Plume Cycle IR Parameter (PCIR) was developed under Contract N00014-74-C-0074, as a cooperative venture between the USN, Office of Naval Research and USAF/ASD-XR (Ref. 1). This technique represents peak plume emissions in two wavelength bands (1.8-2.7μm and 3.9-4.8μm) defined as functions of engine cycle parameters. A companion effort developed under the same contract (C-0074) provided an algorithm for engine Hot Part Emissions, the Cycle IR Parameter (CIR).

PIREP represents the next logical step; to develop a computer routine to express these prediction methods.

II. GENERAL DESCRIPTION

A. PIREP System

PIREP (Preliminary Infrared Radiation Emissions Program) is a computer program module for rapidly generating turbine engine IR emission characteristics. It is compatible with aircraft engine performance decks used by the Government. The program operates in two parallel modes: it can be activated from a cycle deck or from an independent executor routine. PIREP has three degrees of complexity as indicated schematically in Figure 1.

Two extensions to the basic PIREP routine are available to study lockon ranges, suppression concepts, and different wavelength bands or missiles. These can be activated through the cycle deck but are more apt to be used with the independent executor routine. The parameters that can be studied are range, aspect angle, elevation angle, exhaust nozzle shape ratio, and hot parts suppression by cooling, coating and hiding of the hotter elements.

Output may include plume and hot parts attenuated irradiance, lockon range, view factors and projected areas, and spectral distribution of plume emissions and plume/atmospheric transmissivity.

The basic module calculates peak plume and peak hot parts in the 1.8-2.7μm and 3.9-4.8μm wavelength bands for source only. Two extensions to the basic PIREP routine are available to study lockon ranges, suppression concepts, and different wavelength bands or missiles. These can be activated through the cycle deck but are more apt to be used with the independent executor routine. The parameters that can be studied are range, aspect angle, elevation angle, exhaust nozzle shape ratio, and hot parts suppression by cooling, coating and hiding of the hotter elements.

Output may include plume and hot parts attenuated radiance, lockon range, view factors and projected areas, and spectral distribution of plume emissions and plume/atmospheric transmissivity.

Extension I is restricted to the same two wavelength bands but has options to compute:

- IR signatures for plume and hot parts at range as well as source.
- Lockon range for representative missile characteristics
- Simple plume and hot parts suppression capability.

Extension II has, in addition, options for:

- other wavelength bands
- spectral signatures
- simple schematic engine configurations for suppression evaluation.

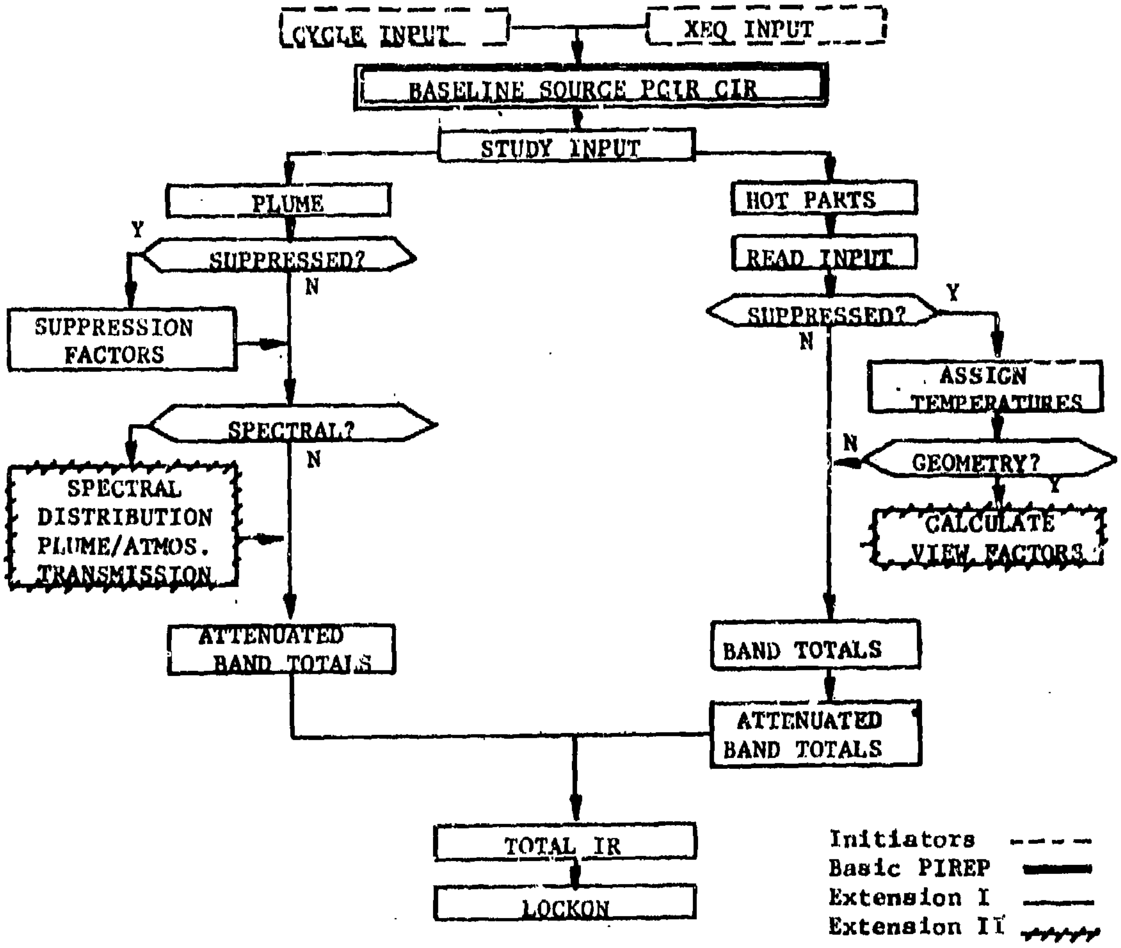


Figure 1. Schematic Diagram of PIREP System

PIREP, a fast prediction method for IR emissions, has been developed for use during configuration definition and preliminary design studies. Potential IR emissions for a wide range of engine and cycle conditions can be estimated quickly at little cost. The program can be easily incorporated into an engine cycle deck or it can be operated independently. The design engineer can now compare the relative vulnerability to IR guided missiles of different engines or aircraft during any phase of design, development, or evaluation.

Little knowledge of IR countermeasures (IRCM) technology is necessary to use PIREP for comparing one engine cycle against another or for preliminary suppression evaluations. As a design engineer becomes more conversant with the problems involved, it is expected he will use more and more options available in the PIREP program and his knowledge and judgement will further increase.

Preliminary studies and evaluations can be made without reference to the IR expert. In this regard, it is important to understand that PIREP provides preliminary estimates only. Before any final decision or commitment on achievable IR levels is made, a detailed study of the IR problem should be performed by more sophisticated techniques and more knowledgeable personnel. These studies, however, fall into the final selection phases and in no way diminish the importance of the preliminary evaluations.

It must be emphasized that the IR signatures estimated by PIREP are good approximations. They are useful, quick estimates for early study purposes to identify critical design parameters, to develop data and to identify gross disparities between types of engine cycles. Therefore, PIREP is useful during configuration definition and the preliminary design phases for the initial screening of engine cycles and the selection of engines to be further studied in more depth. Once the designs are narrowed down further to a few engines, then it may be desirable to use the more accurate IR prediction models.

B. Applications

The basic source plume and hot parts computation, PCIR numbers, can be included directly into a cycle deck and can be output along with the other parameters during cycle studies without penalty since it uses less than 1K storage. The algorithm for estimating plume emissions has been derived from Reference 1 by regression analysis of results from a more sophisticated analytical model (SCORPIO IIIA, Ref. 2). Hot parts emissions are evaluated in this basic module using the exit area and Planck's blackbody emission equation.

During the PIREP development period two studies have been conducted which demonstrate the advantages of PIREP:

- o Basic Engine Parametric Study
- o Advanced Engine Design Study

Neither study would have been done prior to the development of PIREP. The low operational cost of using PIREP made both studies feasible. Herein lies the real advantage of this new analysis tool; studies related to IR and previously financially impractical, can now be made.

Engine Parametric Study

A lack in parametric data has limited the gas turbine engine engineer in relating IR effects to engine cycles. The cost of operating the sophisticated "SCORPIO III" type of computer programs has made parametric studies impossible. Therefore, the basic data of how infrared signatures vary with engine cycles has not been available to the designer. The development of PIREP provides an analysis method that has been used for pseudo-typical parametric study of a configuration definition type.

The study was conducted to establish basic IR trends related to typical engine cycles. The study included engine cycle types (turbojets, separated flow turbofans and mixed flow turbofans); turbofan bypass ratio (1.0 and 2.0); turbine inlet temperature (2000, 2500 and 3000°F); overall cycle pressure ratio (10, 20 and 30); altitude/Mach Number variations (sea level static, sea level/Mach 1.0, 25,000'/Mach 1.0 and 2.0, and 50,000'/Mach 1.0 and 2.0); and engine power conditions (Military and maximum afterburning). The engines were initially sized for a specific weight flow at selected mission points, the engines were scaled to a common net thrust.

A sample of the results is shown in figure 2 to illustrate the usefulness of this study and the type of trend data being developed. This data relates to an advanced plume/hot parts seeker missile threat. The top graph shows the trends of peak hot parts IR level as a function of engine cycle type and bypass ratio. For a turbojet or separated flow turbofan cycle, the hot parts IR level is relatively constant, the turbojet being the lowest. The hot parts emissions for a mixed flow turbofan are higher and increase with increasing bypass ratio because of the larger exhaust area. However, the hot parts IR levels for both the separated flow and mixed flow turbofans can be reduced by effective use of the fan air to cool the hot parts to an IR level below that of the turbojet with no significant effect on performance or weight.

The trend results for peak plume IR level shown in the lower graph of Figure 2 are impressive. The turbojet and separated flow turbofan show an almost constant peak plume IR level regardless of bypass ratio. However, the mixed flow engine cycle yields a considerable reduction in plume IR level with increasing bypass ratio because of the reduction in nozzle exit temperature as more fan air mixes with the hot core gas. In the parametric

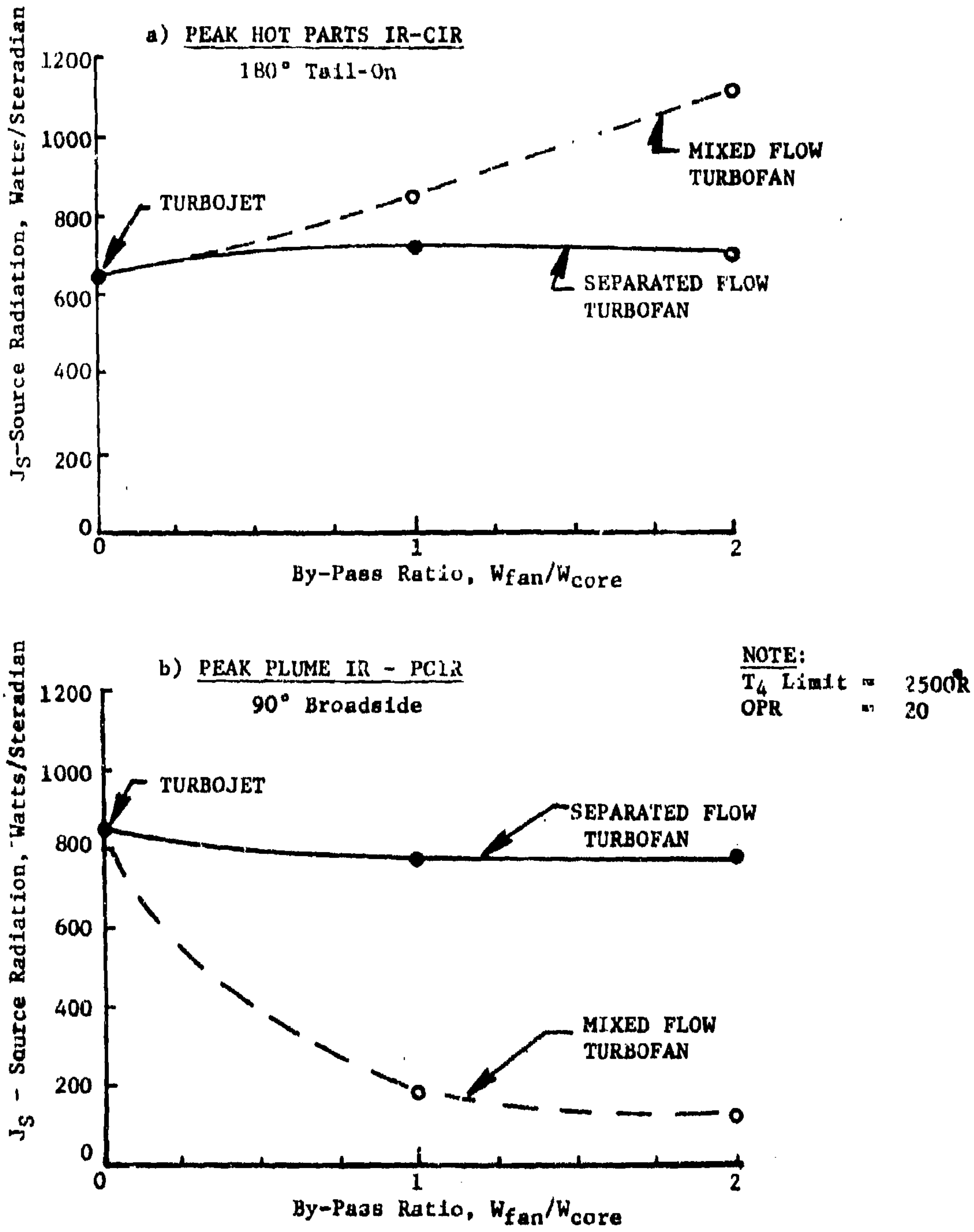


Figure 2. Comparison of Hot Parts and Plume IR levels for Sea Level, Mach 1.0, 15000# Net Thrust Engine Operating at Military Power in the 4.0-4.8μm Missile Detector Interval

study, the reduction in plume IR level for a bypass ratio of two from the separated to the mixed flow cycle is about 85%; engine tests of bypass ratio two turbofan engines have demonstrated a similar order of magnitude reduction.

Using only the trends shown in Figure 2, the engine designer would select the high bypass ratio mixed flow turbofan. However, in a total aircraft study, he would have to consider aircraft take-off gross weight, maneuverability, fly-away cost, ECM/IRCM required, life cycle cost and survivability. It is this total system integration that will determine the final design selection and PIREP can now provide the IR trends needed to make these decisions.

Advanced Engine Design Study

During the past year, PIREP has also been utilized on an advanced engine design study. In the past, IR would not have been considered on an engine demonstrator program of this type for two reasons.

1. Since the weapon system to utilize this new engine type is not even conceived, there are no survivability requirements.

2. The cost of calculating the hot parts and plume IR levels had been too excessive.

However, because survivability against IR guided missiles is receiving more emphasis and because PIREP was under development, it was decided to evaluate the IR trends for the various cycle types, exhaust system designs and nozzle types being studied. The results of the study are not pertinent here, but the cost savings that was realized is significant. These studies required calculation of engine hot parts and plume IR levels for 192 engine cycle conditions. The infrared calculations were made using PIREP. The total calculation time spent on the Honeywell 6000 computer was about 3 minuts (ten dollars). If these same studies had been made using the more accurate analysis tools (SCORPIO III) the computer cost would have been approximately $12,000. Also the task would have taken more manhours of an IR analyst and a much longer time (six months compared to three weeks). Obviously one could say that considerable cost savings had been realized. However, the most important point is that without PIREP the study would not even have been attempted.

C. Analysis

The analytical models developed for PIREP will be discussed in the following paragraphs. Some of the analytical models used in PIREP were developed for the SCORPIO III computer program. These analyses will not be redeveloped here but only mentioned because they have been fully documented in Ref. 3.

1. Basic Peak Hot Parts Emissions

Means of estimating jet engine hot parts source infrared emissions (CIR Parameter) with reasonable accuracy has been available for some time (see Ref. 1). The exhaust exit total temperature, EGT or T_8, and throat area A_8, used directly in Planck's blackbody emission equation have correlated well with measured infrared data.

The relationship being used is

$$\frac{J_{S_0}}{A_8} = \int_{\lambda_1}^{\lambda_2} \frac{76805 \qquad d\lambda}{(\lambda T_8)^5 \left[e^{\frac{-25884}{\lambda T_8}} - 1\right]}$$

for each wavelength band. A comparison of this result with actual engine results is shown in Fig. 3 for IR source per unit area as a function of EGT for the critical 3-5μm region.

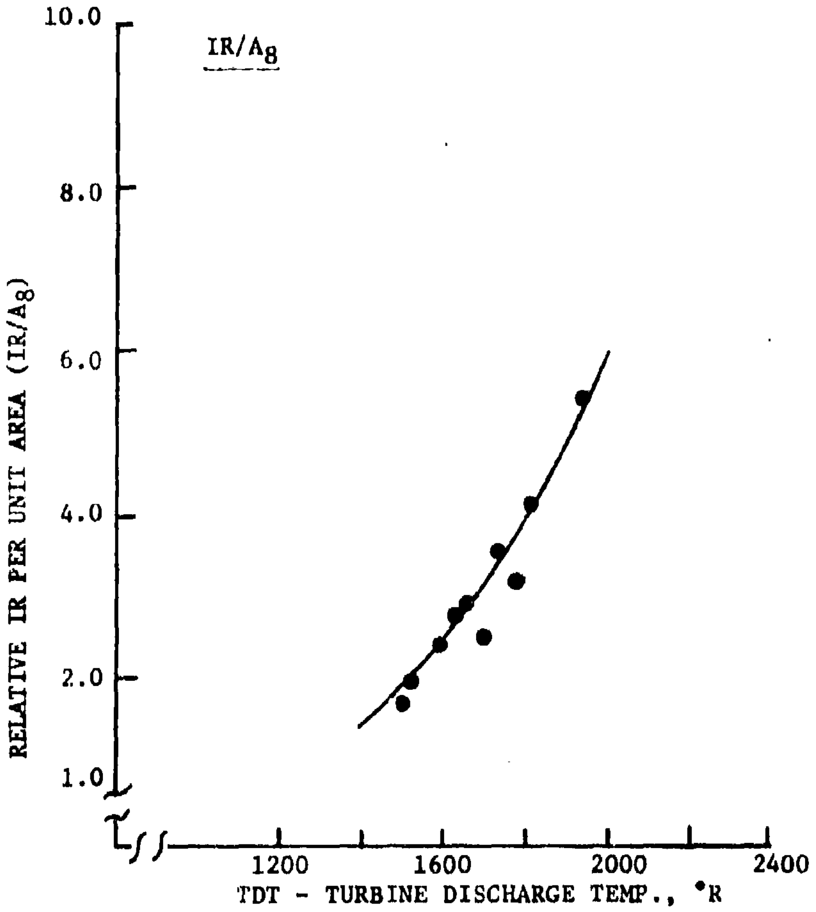


Figure 3: Hot Parts Emissions For Actual Production Engines

2. Basic Peak Plume Emissions

A prediction technique for plume emissions (PCIR Parameter) that is fast and reasonably accurate was developed in Reference 1.

The relationships developed are given as:

$$J_{S0}\ (1.8\text{-}2.7\ ) = \frac{T_s^{2.642}\ P_r^{0.692}\ A_9^{1.286}\ V_e^{0.0667}\ P_a^{0.806}}{(P_r-1)^{0.1245}\ e^{7592/T_s}\ e^{19.766}}$$

$$J_{S0}\ (3.9\text{-}4.8) = \frac{T_s^{1.2185}\ (P_r)^{0.712}\ A_9^{1.205}\ V_e^{0.0606}\ P_a^{0.367}\ V_9^{0.023}}{(P_r)^{0.1595}\ e^{4676/T_s}\ e^{8.196}}$$

here, J_{S0} = Source band emissions, watts/steradian
T_s = Static temperature at exit, °R
P_r = Exhaust pressure ratio
A_9 = Fully expanded exit area, in^2
V_e = External flow velocity, ft/sec
P_a = Ambient pressure psia
V_9 = Secondary flow velocity, ft/sec

Correlation studies and regression analysis were made to develop these preliminary design estimates of peak plume infrared radiation for a variety of gas turbine engine cycles. The cycle types included turboshaft, turbojet, separate flow turbofans and mixed flow turbofans. The operating ranges included sea level static and cruise conditions and inflight cruise and afterburning cases. These cases were initially calculated by a sophisticated computer program (SCORPIO III, Ref. 2). The IR results were then correlated by fundamental cycle parameters to yield the prediction relationships (PCIR numbers) for source radiation in the 1.8μm to 2.7μm and 3.9-4.8μm wavelength bands.

The numbers have been compared to the original SCORPIO calculations. For the cases studied the average deviation between the two results was less than 20% (see Figures 4 and 5). The PCIR numbers are used in the present PIREP program. It must be remembered that these results were developed to cover a large range of radiation predictions (spanning 6 orders of magnitude). The numbers are not accurate enough to use for refined comparisons in the final stages of engine analysis. For these purposes, the more sophisticated analytical tools, such as SCORPIO III, must be used.

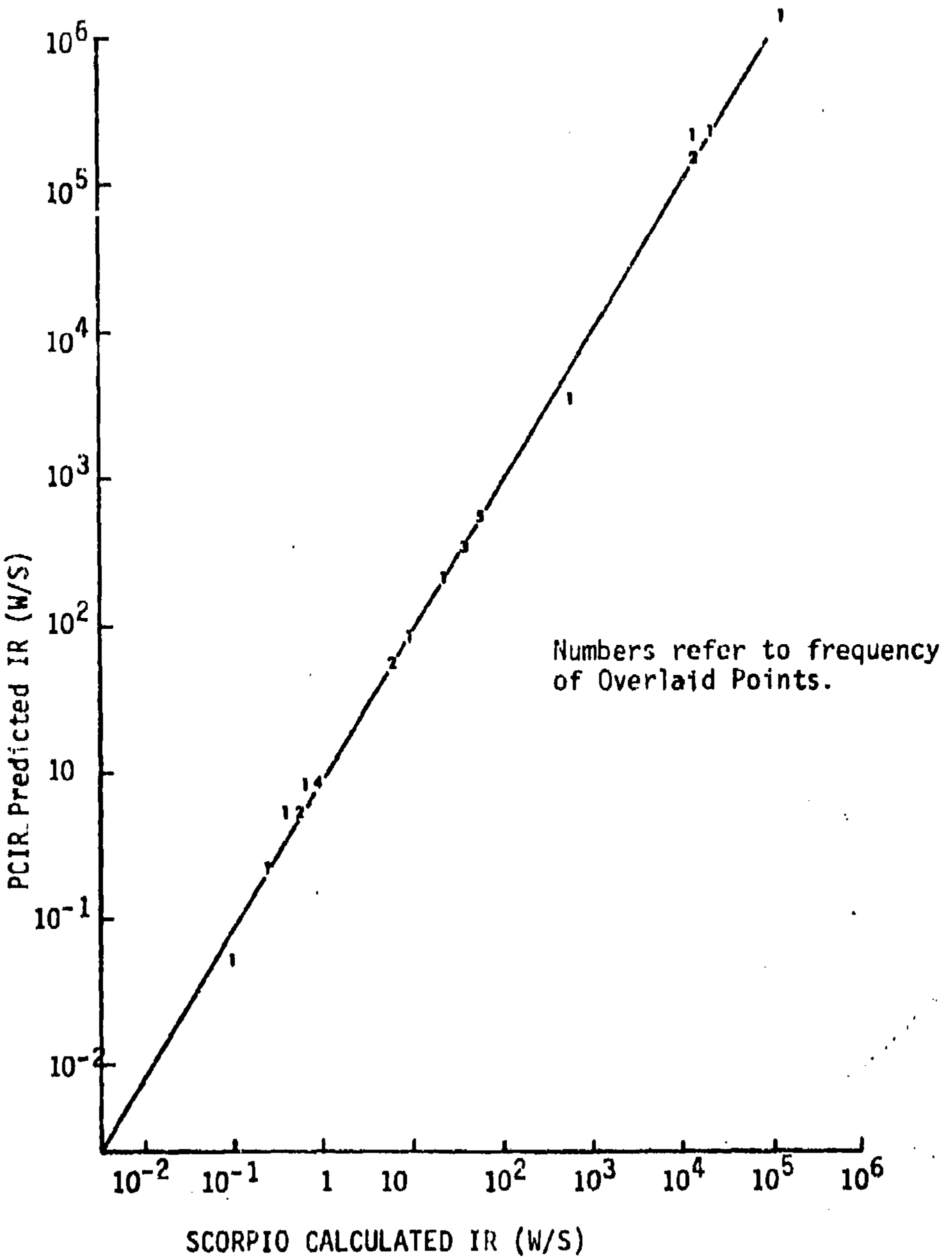
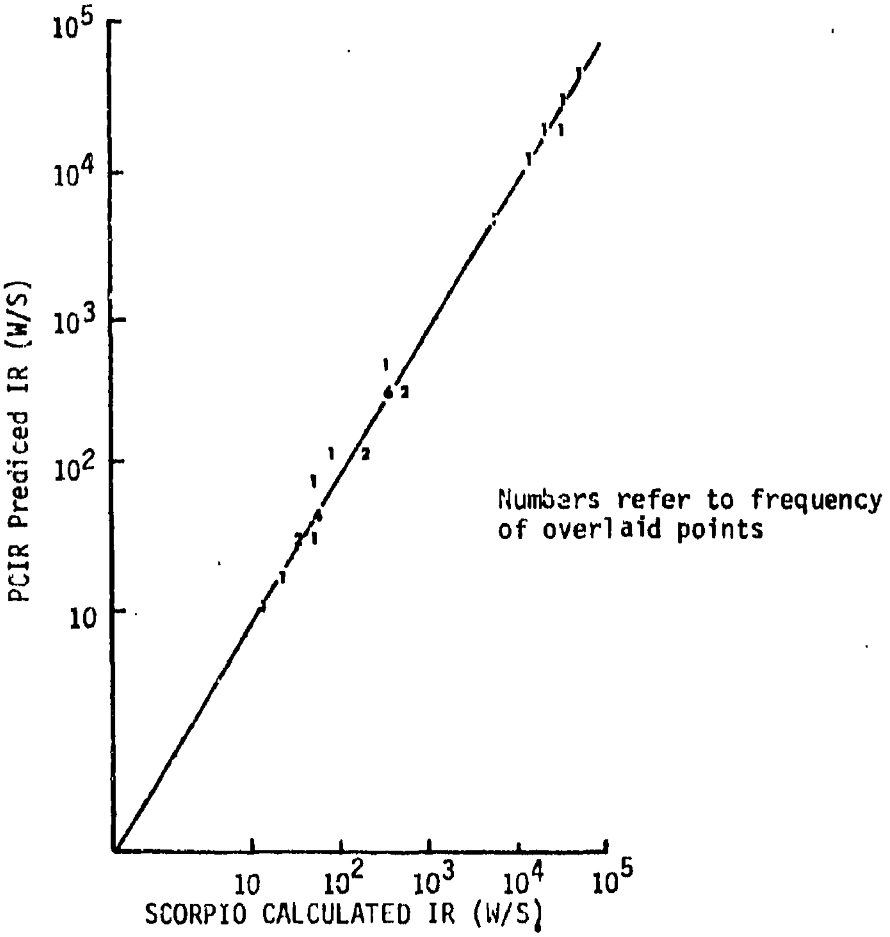


Figure 4: Comparison of PCIR Predicted and SCORPIO Calculated IR Plume Source Radiation at 90^0 Aspect Angle for 1.8-2.7μm Wavelength H_2O Band.



Numbers refer to frequency of overlaid points

Figure 5: Comparison of PCIR Predicted and SCORPIO Calculated IR source Radiation at 90° Aspect Angle for the 4.0-4.8μm Wavelength CO_2 Band.

3. Atmospheric Transmissivity

Hot Parts

Transmission of hot IR emissions through the atmosphere depends only on the ambient pressure, the path length and the temperature of the source emissions. PIREP assumes the relative humidity to be 25% for all cases, and to the accuracy of the PIREP approximations, the ambient temperature is not a factor.

A number of SCORPIO calculations were made for the atmospheric transmittance of hot graybody sources at source temperatures ranging from 500°R to 3000°R at altitudes of 0, 15K and 30K feet and atmospheric ranges of 250, 1K, 5K, 10K and 50K feet. The resultant transmissivities, τ, have been expressed as functions of ambient pressure, path length and source temperature.

$$\tau_{1.8-2.7} = (.57-.09\,PX)\quad 1-e^{0.001833(122-T_{S_0})}$$

$$\tau_{3.9-4.8} = .64 - .08PX$$

where

$PX = \ln (Pa^2 R_C)$

P_a = ambient pressure, atmos.

R_G = range, K feet

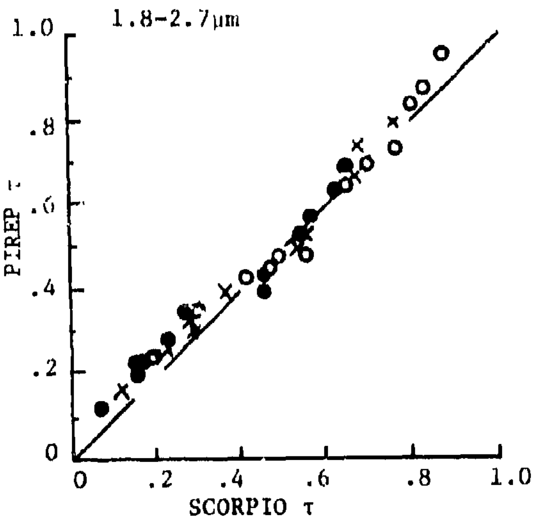
T_{S_0} = source temperature, °R (Radiation Averaged)

The plot of the PIREP transmissivity versus the SCORPIO transmissivity of the hot parts emissions is shown in Figure 6. Perfect agreement would result as the 45° straight line through the points.

$$\frac{J}{J_{S_0}}\ (1.8-2.7) = \left(R_G + \frac{.1875}{R_G}\right)^{-4.4/R_G^{0.2}/(T_8/1000.)^{0.75}}$$

$$\frac{J}{J_{S_0}}\ (3.9-4.8) = \left(R_G + \frac{.1875}{R_G}\right)^{-3300/R_G^{0.13}/T_8}$$

where RG = (RANGE + 250.)/1000.



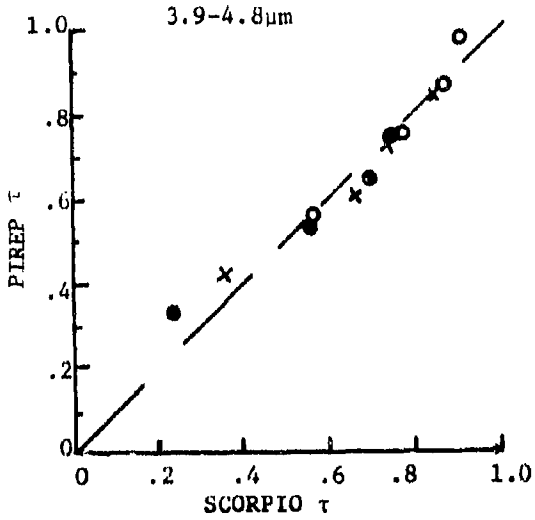


Figure 6. **Comparison of Atmospheric Band Transmissivities of Hot Parts as Computed by PIREP and SCORPIO IIIA**

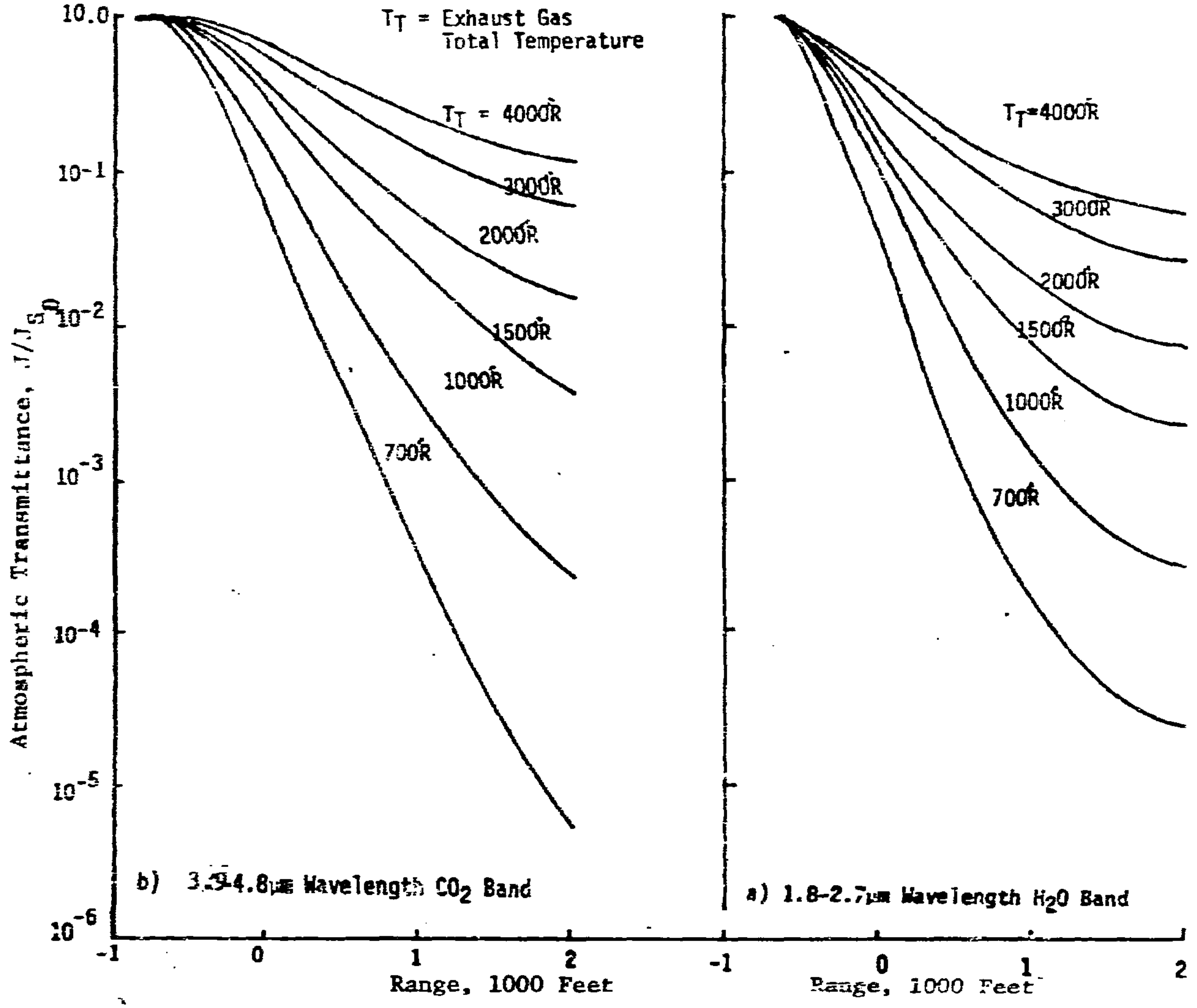


Figure 7: Atmospheric Transmittance of IR Source Radiation at 90° Aspect Angle for 1.8-2.7μm H_2O and 3.9-4.8μm CO_2 Wavelength Band for Various Exhaust Gas Total Temperatures

4. Missile Lockon Range

An algorithm for calculating missile lockon range was developed for the SCORPIO III computer program, Ref. 2, and is used in the PIREP program.

The signal to noise ratio for a given range from the target to the missile is given as:

$$\frac{S}{N} = \int_0^\infty \frac{\frac{J_\lambda \tau_{\lambda p}}{R^2}}{NEI} \, d\lambda$$

where J_λ is the target radiation

τ_{p_λ} is the plume/atmospheric transmissivity

R is the range

NEI is the noise equivalent input of the missile optics, electronic components and guidance signal processor.

In general, the S/N ratio, necessary for missile lockon is known. If the available S/N is calculated for a series of ranges between the target and missile, the range at which lockon can occur can be obtained by interpolation. This interpolation is made between the log of S/N since the log of S/N varies with the log of range in a nearly linear manner.

5. Hot Parts Suppression

The program, SIGNIR, obtained from LTV, Reference 4, and incorporated into SCORPIO IIIA, Ref. 2, has been stripped down and streamlined for use in PIREP. For this application, a maximum of 6 surfaces can be represented for reflection/emission studies. Simply dividing the exhaust area into a hot part and a cooler part can also be evaluated. The results of this portion of the program are estimates only. Generally, many more than 6 surfaces are needed to adequately represent an exhaust system for IR purposes since large temperature gradients (50-1000°R) can exist along many engine components and a temperature difference of 50°F will have a significant effect on the IR signature. To summarize, the use of this option is for feasibility studies only and should not be used to obtain final "quotable" signature information.

6. Effect of Nozzle Shape on Plume Emissions

The most effective way to reduce the plume IR emissions is to reduce the exhaust gas temperature by mixing the hot core gas with cooling bypass air. This approach is available for study in PIREP by altering the basic cycle conditions.

For some applications, the bypass flow is too small to reduce the temperature sufficiently. The next best method for reducing plume emissions appears to be by changing the shape of the exhaust cross section from round to rectangular keeping the same flow area.

Limited studies of round jets and comparable rectangular jets yields the following information:

(1) The emissions viewed from the narrow side of the rectangular jet are much smaller than those from the broad side because the projected area is smaller. An opposing effect resulting from the increased optical depth is subordinate in most full scale engine applications. Increases due to the optical depth has, however offset the reduction to the smaller area in some small scale tests.

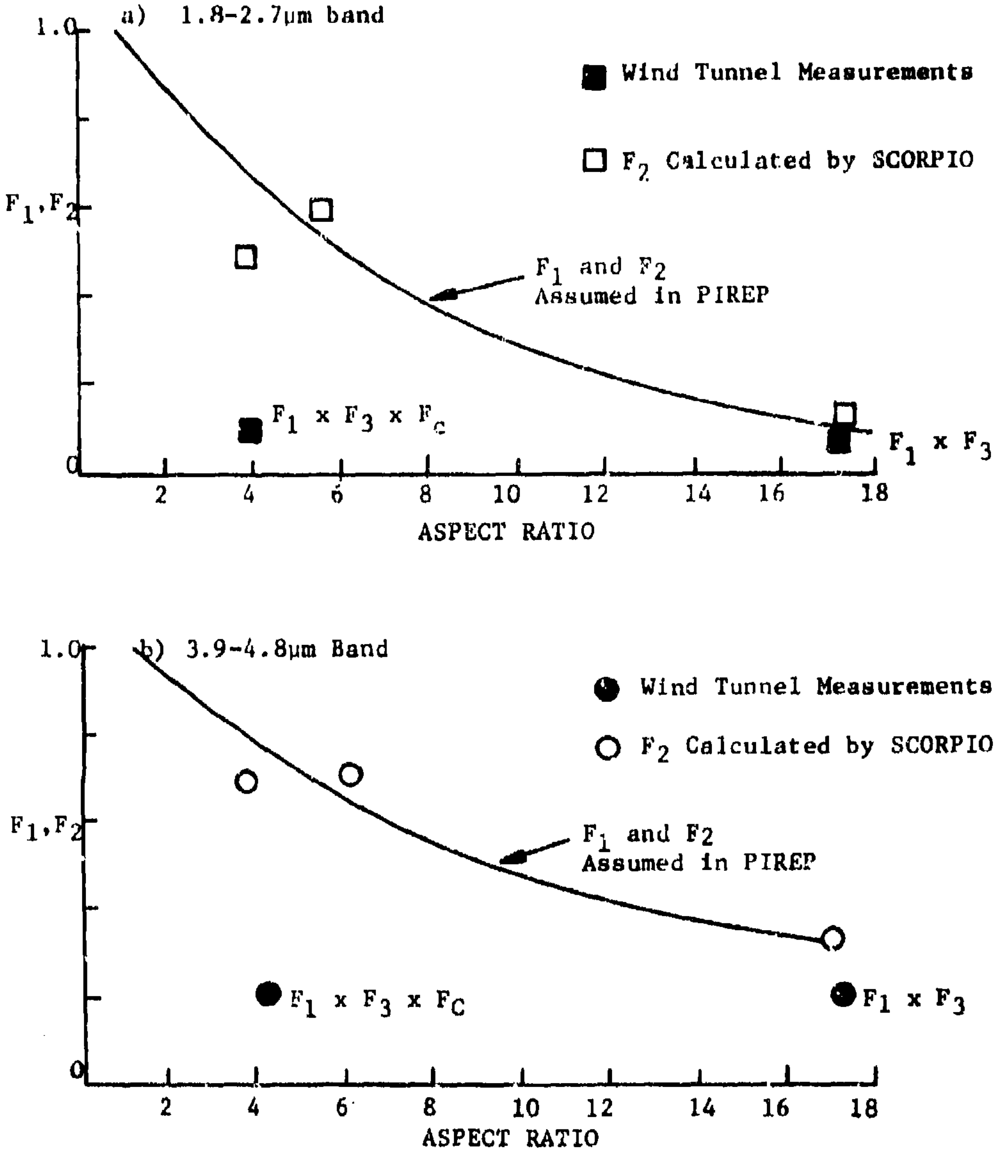
(2) The core length is much shorter for rectangular jets than for round jets with the same flow area. In static tests, this result has been substantiated by the experimental data.

(3) In flight, the core length is even further shortened by eddies generated in the corners of the rectangular nozzle which help to wash out the core region.

These factors seem to provide qualitative explanations for the results presently available. From these existing beginnings of a new data base, estimates have been made of the effects described above as functions of the aspect ratio of the rectangular exits. These estimates, Figures 7a and 7b are tabulated in PIREP. It is recommended that the program be updated periodically as the data base grows and becomes available.

7. Spectral Calculations

Spectral plume properties are needed to extend PCIR results to other wavelength intervals and to add plume absorption to atmospheric absorption in predicting attenuated hot parts emissions. For specific applications the wavelength bands supplied internally by PIREP, may not be appropriate and interpolation directly with other bands or even parts of the same band can only be done spectrally becuase of the sharp variations of emissions with wavelength. Also the absorption of hot parts emissions by the plume plus atmosphere will be somewhat higher than for atmosphere alone



F_1 = Broad/Round

F_2 = Narrow/Broad

F_C = Crosswind Effect

F_3 = .7 Inflight

= 1.0 Static

Figure 8: Representation of Plume Suppression Factors

because the hotter plume absorbs in a broader band than does the cooler atmosphere. This is especially true at near tail-on aspects where there is a long plume/core path between the source and the observer.

Unlike solid surfaces, gases do not emit in a continuous spectrum, but in discrete lines distributed about a band center. The wavelength location of the emission lines at a hot gas correlate with the location of the absorption lines of the same gas at a colder temperature. Also, some of the molecules of hot gas are in a more excited state and emit energy in regions further removed from the band center, effectively broadening the band or in new bands not activated by the colder gases. For this reason the regions of interest that contains a whole band, only one wing (½ the band) or more than one band behave entirely differently as functions of range, temperature and concentration of emitting species.

To approximate the behavior of a plume at other than reference wavelength bands, the following assumptions have been made (Refer to Fig. 8):

- Since the core region of a plume emits a significant percentage of the plume radiation, characteristics of the emissions are the same as those of a single ray through the core region.

- The self attenuation of the plume can be approximated by a mixing region that has the averaged properties of the plume and atmosphere.

- The segment of the ray lying within the plume is approximated by the radius of a fully expanded plume at the exhaust exit divided by the sine of the aspect angle (for angles less than 5 degrees, use 5 degrees).

- The segment of ray lying within the mixing region is equal to the core segment for acute aspect angles and equal to the product of the cosine of the supplementary angle (π-ASP) and the radius when the aspect angle is obtuse. For the rectangular exhaust shapes, the radius is replaced by a dimension dependent on the elevation angle, the height and the width.

- The emissions per unit area for the ray described above is assumed to have the spectral characteristics of the entire plume. The attenuated PCIR numbers in the reference band are used to adjust the level of emissions.

The spectral distirbutions are needed internally to extend results to other than the two basic wavelength bands. Normally the design engineer will have no use for the spectral radiation distributions. However, if he needs them they are available.

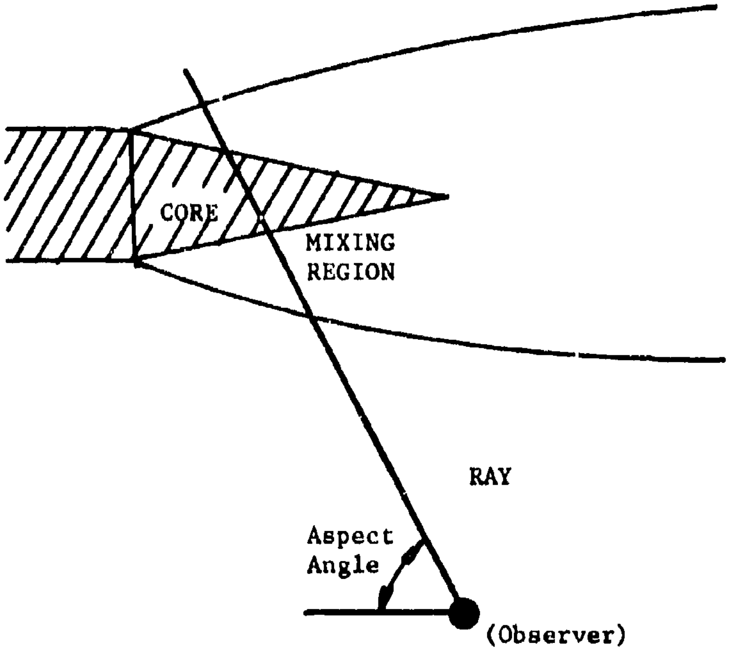


Figure 9. Schematic Representation of Plume

8. SCORPIO-IIIA Analytical Models

Many of the PIREP subroutines were taken directly from SCORPIO-IIIA The analysis associated with these routines is available in Reference 3 and is only itemized here.

Subroutine CEMS-EMIST

The transmissivity along a ray depends on the molecular behavior of the gases contained in the ray. The analysis is based on fundamental quantum theory principles and results of the calculations compare well with homogeneous and non-isothermal measured emissions.

Subroutine VIEW

The subroutine VIEW and its subordinate routines calculate view factors between each surface and every other surface.

A new factor, F_{12} is the net fraction of the radiation which leaves surface A_1 and is absorbed by Surface A_2. The viewfactors are the key to any radiation interchange. The analysis involves subdividing each surface into small facets and integrating numerically an expression of the form:

$$F_{12} = \frac{1}{A_1} \int_{A_2} \int_{A_1} \frac{\cos\theta_1 \cos\theta_2 \, dA_1 \, dA_2}{\pi\rho^2}$$

where θ_1, θ_2 are angles between the surface element normals and the line between the two elements and ρ is the distance between the two elements.

Subroutine REDII and VECANG

The visible projected areas for each aspect angle are calculated by assuming a small elemental area situated 1000 ft. from the exhaust exit plane in the aspect angle direction. The logic is similar to that used in subroutine VIEW.

Subroutine SIRER

The total radiation leaving any surface is a combination of the direct emissions from that surface and the reflection of emissions originating from all other surfaces. Subroutine SIRER determines the radiation coefficients which relate the surface from which the radiation is visible to the surface from which it originated.

D. Sample Problems

Discussion

A series of seven test problems were prepared to exercise all of the options available in basic PIREP and its extensions. The input and output are in the PIREP User Manual (Ref. 5). The test problems are in a sequence that might be used in actual practice. The complete exercise involves seven problems.

1. Comparison of two different engines at several flight conditions.
2. Evaluation of preliminary signature and lockon for one engine - one flight condition (Engine, I; condition, 2).
3. Evaluation to plume suppression capabilities for condition I-2.
4. Preliminary study of hot parts suppression.
5. Evaluation of two engine configurations for the same cycle for various cooling and coating schemes.
6. Study of spectral signature lockon for the selected suppressed configuration.
7. Evaluation of lockon for advanced missiles including airframe emissions external to the exhaust system.

Each of these test problems was handled as if it were a real problem in evaluation of engines and cycles during preliminary design. The details of the input/output are presented in the PIREP User Manual (Ref. 5). Only a brief discussion of the problem content is included here.

The cycle data used for problem 1 and the output peak infrared radiation numbers are given in Table 1. The cycle parameters used in PIREP are:

T7	exhaust exit total temperature, °R
T5	turbine exit total temperature, °R
Tamb	ambient temperature, °R
P8	exhaust exit total pressure, psia
A8	throat area of exhaust, in^2
XM	flight Mach number
V19	secondary flow velocity, ft./sec.
FAR	fuel-to-air ratio
ALT	altitude, K feet

Engine I, cycle 2, was selected as the basic cycle for further study For problem 2, complete signature and lockon ranges for the basic cycle were calculated (see Table 2). The principal problem areas, as might be expected are hot parts tail-on and plume broadside.

In problem 3, the effect on plume emissions of nozzle shaping was studied. The results of the study are presented in Table 3 for aspect ratios of 1 (round jet), 4 and 10 at elevation angles of 0, 45, and 90. For an aspect ratio of 10, there is an 86% reduction in plume emissions viewed from the broadside and a 97% reduction viewed from the narrow side.

Table 4 presents the results of hot parts suppression schemes, evaluated at 0° and 30° aspect angles and at source and 50K feet range.

The first four lines of output in Table 4 are from problem 4 where the exhaust area was represented by two areas at temperatures of 1500°R and 2008°R in differing proportions, X being the portion allotted to 1500°R. The second 4 rows are results for a C/D nozzle with various cooled and coated surfaces. The last four rows are results for an equivalent plug nozzle configuration for various cooled and coated surfaces. These configurations are described in detail in the User Manual.

Configuration B2, which is a plug nozzle with the visible surface of the plug and nozzle flap cooled to 1100°R, was selected as the most effective configuration. There is a 90% reduction in hot parts emissions at 0°. At 30°, the reduction is just over 50%.

In problem 6 the lockon ranges for the suppressed configuration were calculated at 0, 30 and 60 degrees and compared with the unsuppressed results (see Table 5). The lockon ranges were reduced by more than ½ in most cases.

Problem 7 merely exercise options not used in the previous set. It determines lockon ranges for entirely different missiles and includes an estimate of airframe emissions in the evaluation.

Table 1. Cycle Data Input and Peak IR Emissions Output for Problem 1.

Input Conditions

Condition	ENGINE I			ENGINE II		
	1	2	3	1	2	3
T7	1415	1388.3	1401.8	1992	2008.1	2031.4
T5	1992	2003.1	2031.4	1992.	2008.1	2031.4
Tamb	520.	520.	380.	520.	529.	380.
P8	42.53	56.82	20.64	42.696	55.36	19.774
Pamb	14.7	14.7	1.682	14.7	14.7	1.682
A8	511.3	534.59	529.8	320.7	311.9	298.1
XM	0	1.0	2.0	0	1.0	2.0
V19	0	0	-	1540.7	1805.7	2353.1
FAR	.0126	.01080	.0099	.0252	.0243	.02356
ALT	0	0	50	0	0	50
Results						
PCIR1	25.	17.	1.0	205	241	17
PCIR2	362	349	107	1028	1410	671
CIR1	1836	2010	2127	1151	1171	1197
CIR2	1211	1298	1334	759	757	750

Table 2. Signature and Lockon Ranges for Basic Cycle

Aspect Angle	Distance (K Ft.)	1.8-2.7 Plume	1.8-2.7 Hot Parts	3.9-4.8 Plume	3.9-4.8 Hot Parts
0°	0	1.4	2010	30.4	1298
	5	.02	828	1.25	664
	50	.003	424	.113	426
	100	.003	303	.074	353
Lockon Range (K Ft)		30.508		86.9	
30°	0	8.3	174	175	1124
	5	.14	217	7.18	575
	50	.02	367	.65	368
	100	.015	262	.43	305
Lockon Range (K ft)		28.7		86.9	
60°	0	14.4	1005	303	649
	5	.24	414	12.4	332
	50	.031	212	1.12	212
	100	.026	151	.736	176
Lockon Range (K ft)		22.7		86.9	
90°	0	16.6	0	349	0
	5	.27	0	14.4	0
	50	.035	0	130	0
	100	.030	0	.85	0
Lockon Range (K ft)		2.3		12.9	
130°	0	12.7	0	268	0
	5	.21	0	11.0	0
	50	.03	0	.99	0
	100	.02	0	.65	0
Lockon Range (K ft)		2.2		119.	
170°	0	0	2.9	60.7	0
	5	.05	0	2.49	0
	50	.01	0	.23	0
	100	.005	0	.15	0
Lockon Range (K ft)		1.8		7.5	

Table 3. Effect of Nozzle Shaping on Plume Emissions and Lockon Ranges

Elevation Profile	Aspect Ratio	Emissions AT 0 Feet	Emissions AT 53 K Feet	Lockon Range (K Ft.)
	A. 1.8-2.7μm			
0	1.0	17.0	0.03	1.4
	4.0	6.6	0.01	1.0
	10.0	2.3	0.005	0.7
45°	1.0	17.0	0.03	1.4
	4.0	5.7	0.01	1.0
	10.0	1.8	0.024	0.7
90°	1.0	17.0	0.03	1.4
	4.0	3.7	0.008	0.9
	10.0	0.51	0.001	0.5
	B. 3.9-4.8μm			
0	1.0	349.0	1.3	12.4
	4.0	167.0	0.62	9.7
	10.0	95.0	0.35	8.1
45	1.0	349.0	1.3	12.4
	4.0	152.0	0.56	9.4
	10.0	78.3	0.29	7.6
90	1.0	349.0	1.3	12.4
	4.0	114.7	0.43	8.6
	10.0	37.2	0.14	5.9

Table 4. Hot Parts Emissions for Different Exhaust Configurations

	0°				30°			
Configuration	1.8-2.7		3.9-4.8		1.8-2.7		3.9-4.8	
Range (K Ft)	0	50	0	50	0	50	0	50
X = 0	2010	424	1298	426	1741	367	1124	368
X = 0.25	1583	333	1118	356	1378	289	1117	309
X = .5	1153	242	908	287	1006	210	934	248
X = 1.0	324	59	487	149	263	51	570	130
A 1	2237	473	1416	463	839	176	684	224
A - 2	1125	238	759	248	784	165	678	222
A - 3	1439	305	909	297	746	157	559	183
A - 4	1138	241	730	239	691	146	529	173
B - 1	1851	560	1253	560	2016	425	1314	429
B - 2	100	21	201	66	449	94	386	126
B - 3	66	14	148	48	420	89	341	117
B - 4	27	5	138	45	388	82	331	108

Table 5. Comparison of Lockon Ranges for Suppressed and Unsuppressed Exhaust System

	Test Problem 2 Unsuppressed		Test Problem 6 Suppressed	
Missile No. Aspect Angle	1	2	1	2
0	30.5	118.2	8.2	39.5
30	28.7	111.3	18.5	56.4
60	22.7	86.9	9.5	34.6

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SUPPLEMENTARY

INFORMATION

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ERRATA SHEET, VOLUME I

Page 9;

1. Basic Peak Hot Parts Emissions

Means of estimating jet engine hot parts source infrared emissions (CIR Parameter) with reasonable accuracy has been available for some time (see Ref. 1). The turbine discharge temperature, TDT, T5 and throat area A_8, used directly in Planck's blackbody emission equation have correlated well with measured infrared data.

The relationship being used is

$$\frac{J_{S_0}}{A_8} = \int_{\lambda_1}^{\lambda_2} \frac{76805 \quad d\lambda}{\left[(\lambda T_5)^{5} \; e^{\frac{-25884}{\lambda T_5}} \quad -1\right]}$$

for each wavelength band. A comparison of this result with actual engine results is shown in Figure 3 for IR source per unit area as a function of TDT for the critical 3-5µm region.

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The relationships developed are given as:

$$J_{S_0}\ (1.8\text{-}2.7) = \frac{T_s^{2.642} P_r^{0.692} A_9^{1.286} (V_e+5)^{0.0667} P_a^{0.806}}{(P_r^{0.25} - 1)^{0.1245} \; e^{7592/T_s} \; e^{19.766}}$$

$$J_{S_0}\ (3.9\text{-}4.8) = \frac{T_s^{2.642} P_r^{0.712} A_9^{1.205} (V_e+5)^{0.0606} P_a^{0.367} (V_9+5)^{0.023}}{(P_r^{0.25} - 1)^{0.1595} \; e^{4676/T_s} \; e^{8.196}}$$

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The hot parts emissions is shown in Figure 6. Perfect agreement would result as the 45° straight line through the points.

$$\frac{J}{J_{S_0}}\ (1.8\text{-}2.7) = \left[R_G + .77\ R_G^{0.01}\right]^{-4.4/R_G^{0.2}/(T_8/1000.)^{0.75}}$$

$$\frac{J}{J_{S_0}}\ (3.9\text{-}4.8) = \left[R_G + .77\ R_G^{0.01}\right]^{-3300/R_G^{0.13}/T_8}$$

where RG = (RANGE + 250.)/1000.