INFRARED STUDIES ON THE JET EXHAUST OF A TURBOJET AIRCRAFT*

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In an attempt to evaluate the effective Infrared radiant energy from a conical jet exhaust of a jet aircraft, infrared emission characteristics have been worked out with special reference to guidance and decoy purposes. Suitable infrared absorbing materials used for shielding the infrared emitting skin of the radiating part have also been discussed. Attempts have also been made to evaluate the effective radiation on a detecting system after allowing for the solar radiant heat and also atmospheric absorption.

Any body whose temperature differs from absolute zero (—273°C) is a source of infrared radiation. The radiation of such objects like sea going vessels, tanks, aircraft, rocket and industrial establishments etc are of highest interest for military purposes. In the case of IR radiations no signals or pulses have to be sent, as is done in the case of radar devices in order to discover the source of radiation. It is only necessary to know how to receive and discern among all variform radiations—those rays which arrive from the necessary target. Thereupon, these radiations have to be converted into visible rays or electrical signals which can enter, for instance, the self guidance automatics of the missile[1].

Aircrafts or rockets in flight constitute powerful sources of infrared rays. At low velocities they are radiated directly by the heated up parts of power plants and exhausts. They can be revealed only in the rear hemisphere, and this fact determines the interception tactics with respect to such targets.

With the increase in velocity of flight especially at the transition through the velocity of sound, there begins strong radiation from the heated covering (skin). With the increase of velocity, the intensity of radiation increases. The detection of aircraft is facilitated from other directions in addition to the rear atmosphere when it behaves as a torch of infrared rays at high speed.

A wide variety of specific types of missiles to which IR technique has been applied are air-to-air, ground-to-air, air-to-ground and ground-to-ground missiles. Of these, the most successful application has been to the air-to-air homing missile. For the successful operation of guidance systems, it is necessary to know the infrared radiation from various targets and background of military interest. In the case of jet plane, the efficient IR energy distribution is obtained when it flies at high speed and high altitude. Tremendous power has to be generated to attain these flight conditions.

It is in this connection that it was thought worthwhile to carry out an exhaustive assessment of infrared radiations emitted by the tail pipe or the conical exhaust of a jet plane.

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TURBOJET-ENGINE

Before proceeding into the details of the thermal conditions in the jet exhaust, a brief working[2] of the turbojet (Fig 1) is given below.

The turbojet is an air breathing propulsion engine used in aircraft. Thrust ratings range from a few hundreds to 20,000 lb or more. The engine operates best at high sub-sonic or supersonic flight speeds when the high velocity jet achieves good efficiency.

The turbojet is a heat engine. Air enters the inlet diffuser and is compressed adiabatically in the rotating compressor. Heat is added by burning fuel at constant pressure in the combustor. The hot gas expands in the turbine which drives the compressor further and expansion through the jet nozzle converts the remaining available energy of the gas stream into propulsion power. In some turbojets more heat is added in a chamber called 'after burner' which follows the turbine. This in turn increases the propulsion power output. The inlet diffuser decreases the relative velocity of the incoming air while there is a steep rise of the pressure at the entry in the chamber. The reverse phenomenon happens at the nozzle expansion. For supersonic speeds a converging-diverging passage is required. The axial flow compressor shown in Fig 1 has alternate rows of rotating and stationery blades which compresses the air further.

In the combustor jet fuel, a kerosene like petroleum fraction is sprayed, vapourised and burnt. A typical jet fuel is a gasolene kerosene mixture of boiling range 90 to 250°C and vapour pressure 2.315 mm. Air from the compressor discharge is fed into the combustion space. The turbine nozzles direct the high velocity gas streams against turbine blades mounted on wheels. The gas is turned in the blades and this momentum change imparts energy to the wheels. In the after-burner, V section channels are mounted down stream from the fuel spray bars. These channels produce eddies in the gas stream to promote stable burning and prevent blow out at high altitude.

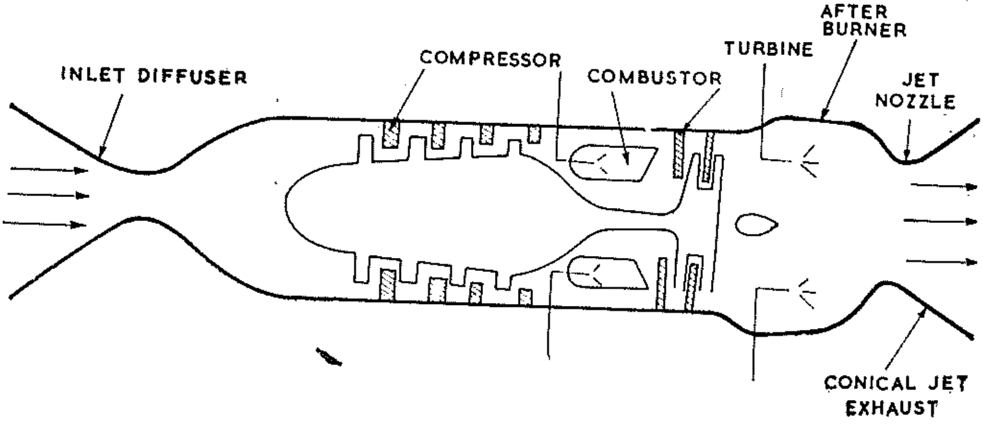

Fig 1—Sketch of the turbojet engine.

A converging jet nozzle of fixed dimension is used for subsonic flight application and a converging-diverging jet nozzle for supersonic flight. The dimensions of the throat and exit may be varied to match the requirements of varying flight speed and altitudes.

CONICAL JET EXHAUST

The object of the present investigations is to assess the nature of IR radiations, its power and intensity at the tail pipe or the conical jet exhaust of the turbojet. A converging-diverging type used for supersonic flight is considered. A typical nozzle cone is shown in Fig 2. The semivertical angle of the jet cone is 25° and the diameter of the jet nozzle is 10 cm and the length of the axis OD from the centre of the nozzle to the centre of the periphery of the cone at section BDC is 75 ft*.

In an attempt to analyse the thermal conditions inside the cone, we assume a temperature gradient set up by the exhaust gases. This gradient from the jet nozzle to the exhaust gases. This gradient from the jet nozzle to the exhaust along the axis is taken to be 1000–400°C. Actual values do not deviate much from the assumed values.

THEORY

The high temperature combustion fuel mixture in the combustion chamber radiates heat strongly to the internal walls of the combustion chamber. As the hot gases move ahead and come out through the jet nozzle, the entire conical surface gets heated. In general, the radiative heat flux increases with increasing temperature, pressure and chamber diameter. Incandescent particles such as carbonaseous soot and light metal oxides produced in the combustion process may easily contribute to the largest fraction of the radiative heat flux.

It is necessary at the out set to define precisely the several types of radiations that may be encountered in the combustion chamber[3]. Thermal radiation is emitted by a hot body (solid, liquid or gaseous) merely by virtue of its temperature. Radiation can be stimulated by non-thermal process as well, such as electron bombardment, X-ray bombardment etc. In a combustor an important non-thermal stimulus for radiation is chemical reaction—the radiation in this case being chemiluminescence. With regard to thermal radiation, it is usually necessary for calculation purposes to assume that equilibrium conditions prevail.

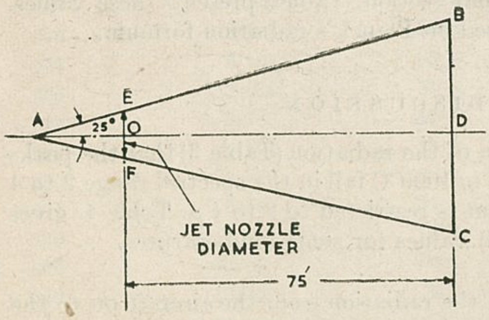

Fig 2—Conical exhaust of turbojet.

The temperature of the gases and the walls of the enclosure containing the radiations should be equal. In practical combustion, however, radiation equilibrium cannot exist, because of the relatively cold walls. But because the radiated energy is only a small fraction of the thermal energy of the gas, the thermodynamic equilibrium in the gas is not appreciably upset and equilibrium theory may be applied.

*These dimensions normally refer to converging-diverging nozzle of a supersonic jet.

Under these circumstances, the conical jet exhaust can safely be assumed to be a radiator less than a 'perfect black body', ie, a grey body. The IR energy distributions have been worked out on the basis of the standard radiation laws, viz, Stefan Boltzman law, Planck's radiation law and the Wiens displacement law[4,5]. While in these computations no specific value for the normal total emissivity of the aircraft surface can be assigned as there are different materials. However, the basic metal aluminium and its alloys (about 20 varieties can be listed[6]), anatentic steels and nickel base alloys have emissivities in the range 0·1 to 0·5 in the temperature range 40 to 600°C. From the numerical tables prepared here the desired energy distribution can be obtained by using the appropriate[6] σ (normal total emissivity) of the material under consideration.

In an ideal case it will be sensible to divide the cone into a large number of sections and to calculate the IR energy distribution at each section. A statistical approach can thus be made to calculate the overall energy distribution from the entire conical jet. Since we have no idea about the variation of surface temperature of the cone from point to point, the entire cone has been divided into fifteen annular sections. Each annular section has a surface width of 5 ft and the average temperature assigned to the sections are on the basis of the four known temperatures.

TEMPERATURE (°C)	DISTANCE FROM O (ft)
400	75
500	50
700	25
1000	0

The entire plane and the surface area of the annular section worked out from the geometry of the cone are given in Table 1.

For each temperature of the section considered, the infrared power (watt/cm^2) over the spectral range 1 to 10 μ was calculated[7] and the total power emitted was obtained by multiplying it by the surface area of the annular section. Table 2 presents these values. Table 3 represents the spectral distribution based on Planck's radiation formula.

RESULTS AND DISCUSSION

It is apparent from the spectral distribution of the radiation (Table 3) that the peaks of IR radiations for the temperature range 400° to 1000°C fall in the spectral range 2 to 4 microns. Hence the major portion of IR output is restricted to 2 to 4 μ. Table 4 gives λ_{max} (μ) and the corresponding W_{max} (watt/cm^2) values for some temperatures.

Before discussing about the effectiveness of the radiation from the aircraft on to the ground or any detecting system in the sky it is necessary to understand the attenuation effect due to the intervening atmosphere between the source (jet exhaust) and the ground and also the solar radiation.

Table 1

Temperature and the areas of the annular section

Range (ft)	Distance from jet nozzle (ft)	Temperature (°C)	Radius of the circular section (ft)	Surface area of the annular strip width ×2 πr (sq cm)
0–5	2·5	960	1·34	$3{\cdot}911 \times 10^4$
5–10	7·5	895	3·69	$10{\cdot}76 \times 10^4$
10–15	12·5	835	6·04	$17{\cdot}62 \times 10^4$
15–20	17·5	775	78·39	$24{\cdot}49 \times 10^4$
20–25	22·5	720	10·74	$31{\cdot}34 \times 10^4$
25–30	27·5	670	13·10	$38{\cdot}23 \times 10^4$
30–35	32·5	625	15·44	$45{\cdot}06 \times 10^4$
35–40	37·5	585	17·79	$51{\cdot}93 \times 10^4$
40–45	42·5	545	20·14	$58{\cdot}78 \times 10^4$
45–50	47·5	515	22·49	$65{\cdot}63 \times 10^4$
50–55	52·5	485	24·84	$72{\cdot}51 \times 10^4$
55–60	57·5	455	27·19	$79{\cdot}36 \times 10^4$
60–65	62·5	435	29·54	$86{\cdot}22 \times 10^4$
65–70	67·5	420	31·89	$93{\cdot}07 \times 10^4$
70–75	72·5	405	34·24	$99{\cdot}83 \times 10^4$

Table 2

Total power emitted by the cone

Temp (°C)	Total emissive power E (watts/cm²)	Surface area of the annular strip (cm²)	Total emissivity (Area of the annular surface × E)	Intensity of radiation (steradian)
405	1·204	99·8	120·1	38·24
420	1·314	93·1	122·1	38·86
435	1·432	86·2	123·4	39·28
455	1·601	79·4	127·1	40·44
485	1·882	72·5	136·5	43·43
515	2·198	65·6	144·2	45·87
545	2·554	58·8	150·2	47·78
585	3·089	51·9	160·0	50·93
625	3·708	45·1	167·2	53·22
670	4·507	38·2	178·2	54·86
720	5·540	31·3	173·4	55·18
775	6·491	24·5	159·1	50·62
835	8·588	17·6	151·1	48·10
895	10·60	10·8	114·5	36·45
960	13·18	3·9	51·40	16·36

Total surface area of the cone $A = 779$ cm

Total emissive power $E = 2073$ (watts/cm²)

Total intensity of radiation $I = 660$ steradian

TABLE 3

SPECTRAL DISTRIBUTION OF POWER EMITTED BY THE CONE

Temperature (°C)	1 μ	2 μ	3 μ	4 μ	5 μ	6 μ	8 μ	10 μ
405	$1\cdot19\times10^{-4}$	$1\cdot622\times10^{-1}$	$7\cdot02\times10^{-1}$	$9\cdot863\times10^{-1}$	$9\cdot418\times10^{-1}$	$7\cdot78\times10^{-1}$	$4\cdot665\times10^{-1}$	$2\cdot764\times10^{-1}$
420	$1\cdot13\times10^{-4}$	$1\cdot868\times10^{-1}$	$7\cdot322\times10^{-1}$	$9\cdot812\times10^{-1}$	$9\cdot232\times10^{-1}$	$7\cdot566\times10^{-1}$	$4\cdot50\times10^{-1}$	$2\cdot656\times10^{-1}$
435	$1\cdot07\times10^{-4}$	$2\cdot114\times10^{-1}$	$7\cdot53\times10^{-1}$	$9\cdot761\times10^{-1}$	$9\cdot046\times10^{-1}$	$7\cdot353\times10^{-1}$	$4\cdot335\times10^{-1}$	$2\cdot548\times10^{-1}$
455	$\cdot99\times10^{-4}$	$2\cdot442\times10^{-1}$	$7\cdot690\times10^{-1}$	$9\cdot693\times10^{-1}$	$8\cdot798\times10^{-1}$	$7\cdot069\times10^{-1}$	$4\cdot11\times10^{-1}$	$2\cdot404\times10^{-1}$
485	$\cdot87\times10^{-4}$	$2\cdot934\times10^{-1}$	$8\cdot21\times10^{-1}$	$9\cdot591\times10^{-1}$	$8\cdot426\times10^{-1}$	$6\cdot64\times10^{-1}$	$3\cdot785\times10^{-1}$	$2\cdot188\times10^{-1}$
515	$\cdot75\times10^{-4}$	$3\cdot426\times10^{-1}$	$8\cdot62\times10^{-1}$	$9\cdot489\times10^{-1}$	$8\cdot054\times10^{-1}$	$6\cdot217\times10^{-1}$	$3\cdot455\times10^{-1}$	$1\cdot972\times10^{-1}$
545	$\cdot63\times10^{-4}$	$3\cdot918\times10^{-1}$	$9\cdot462\times10^{-1}$	$9\cdot387\times10^{-1}$	$7\cdot682\times10^{-1}$	$5\cdot79\times10^{-1}$	$3\cdot125\times10^{-1}$	$1\cdot756\times10^{-1}$
585	$\cdot47\times10^{-4}$	$4\cdot574\times10^{-1}$	$9\cdot68\times10^{-1}$	$9\cdot251\times10^{-1}$	$7\cdot186\times10^{-1}$	$5\cdot22\times10^{-1}$	$2\cdot68\times10^{-1}$	$1\cdot408\times10^{-1}$
625	$4\cdot05\times10^{-3}$	$5\cdot22\times10^{-1}$	$9\cdot77\times10^{-1}$	$8\cdot945\times10^{-1}$	$6\cdot71\times10^{-1}$	$4\cdot765\times10^{-1}$	$2\cdot375\times10^{-1}$	$1\cdot015\times10^{-1}$
670	$3\cdot33\times10^{-3}$	$5\cdot94\times10^{-1}$	$9\cdot75\times10^{-1}$	$8\cdot486\times10^{-1}$	$6\cdot206\times10^{-1}$	$4\cdot342\times10^{-1}$	$2\cdot132\times10^{-1}$	$2\cdot599\times10^{-1}$
720	$2\cdot53\times10^{-3}$	$6\cdot74\times10^{-1}$	$9\cdot73\times10^{-1}$	$7\cdot976\times10^{-1}$	$5\cdot646\times10^{-1}$	$3\cdot872\times10^{-1}$	$1\cdot86\times10^{-1}$	$4\cdot359\times10^{-1}$
775	$1\cdot65\times10^{-3}$	$7\cdot60\times10^{-1}$	$9\cdot71\times10^{-1}$	$7\cdot425\times10^{-1}$	$5\cdot03\times10^{-1}$	$3\cdot355\times10^{-1}$	$1\cdot56\times10^{-1}$	$6\cdot295\times10^{-1}$
835	$2\cdot68\times10^{-2}$	$8\cdot22\times10^{-1}$	$9\cdot48\times10^{-1}$	$6\cdot82\times10^{-1}$	$4\cdot467\times10^{-1}$	$2\cdot914\times10^{-1}$	$1\cdot59\times10^{-2}$	$6\cdot61\times10^{-2}$
895	$1\cdot72\times10^{-2}$	$8\cdot73\times10^{-1}$	$9\cdot08\times10^{-1}$	$6\cdot257\times10^{-1}$	4.00×10^{-1}	$2\cdot578\times10^{-1}$	$4\cdot07\times10^{-2}$	$5\cdot69\times10^{-2}$
960	$\cdot68\times10^{-2}$	$9\cdot28\times10^{-1}$	$8\cdot65\times10^{-1}$	$5\cdot646\times10^{-1}$	$3\cdot492\times10^{-1}$	$2\cdot214\times10^{-1}$	$5\cdot109\times10^{-2}$	$4\cdot69\times10^{-2}$

TABLE 4

W_{max} AND λ_{max} VALUES FOR SOME TEMPERATURES

Temperature (°C)	W_{max} (watts/cm²)	λ_{max} (μ)
405	$9 \cdot 863 \times 10^{-1}$	4
625	$9 \cdot 77 \times 10^{-1}$	3
960	$9 \cdot 28 \times 10^{-1}$	2

The solar radiation reaching the atmosphere of the earth has the following energy distribution :—

2 per cent below $0 \cdot 29$ μ (ultraviolet)

8 per cent below $0 \cdot 40$ μ (ultraviolet)

43 per cent between $0 \cdot 4$ to $0 \cdot 8$ μ (visible)

47 per cent above $0 \cdot 8$ μ (infrared)

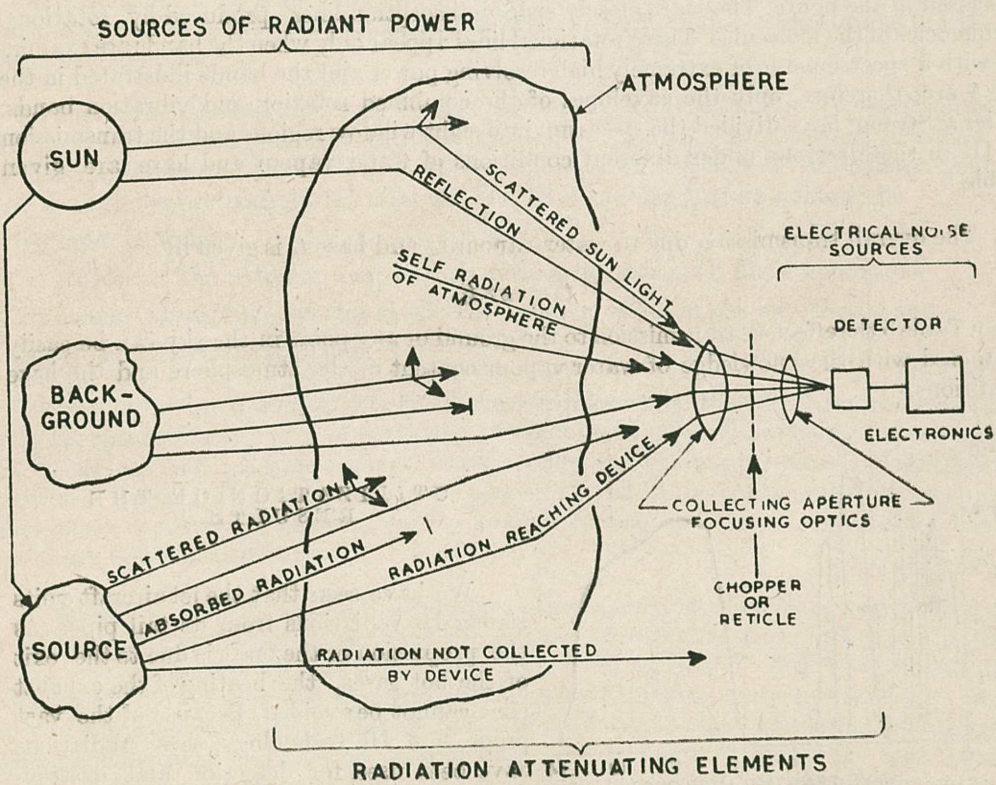

Fig 3—Generalised diagram of infrared process.

Because of absorption of IR radiations by ozone, carbondioxide and moisture and in consequence of Rayleigh scattering the distribution at the earth's surface becomes as follows :--

4 per cent below $0 \cdot 4\ \mu$ (none of which is $< 0 \cdot 29\ \mu$)

54 per cent in the visible range

42 per cent in the infrared

All the infrared radiations[8] at the surface of the earth is below $2\ \mu$.

The effect of the earth's atmosphere must be seriously considered in the design and use of infrared equipment. The infrared radiation incident on an infrared receiver is always extensively changed by the intervening atmosphere. The intervening medium is an inhomogeneous and continuously changing mixture of gases, liquid droplets and particles of solid materials. The gases are water vapour (H_2O), carbondioxide (CO_2), nitrous oxide (N_2O) and ozone (O_3). These gases will absorb and emit radiations as a function, among other things, of the number of molecules present, the wavelength involved and the energy states of the molecules. In actual practice the picture is more complicated. The generalised diagram of the infrared process is shown in Fig 3.

Fig 4 shows the positions on the major bands between $0 \cdot 3\ \mu$ in the ultraviolet to $14\ \mu$ in the infrared. The IR absorption bands of molecules also contain a feature which is not disclosed in the figure. These are closely spaced absorption lines produced by rotational frequencies of the molecules. These rotational lines appear only when the bands are examined with a spectrometer of extremely high resolving power and the bands illustrated in the Fig 4 are, therefore, only the envelopes of the combined rotation and vibration bands. Elder & Strong[9] have divided the spectrum into eight window regions and the transmission of IR in these regions under different conditions of water vapour and haze are given Table 5.

The overall transmission due to water vapour t_w and haze t_h is given by

$$t = t_w \times t_h$$

From Table 5 the effective transmission to the ground or any point in the sky can be easily computed with the knowledge of water vapour content of the atmosphere and the haze conditions.

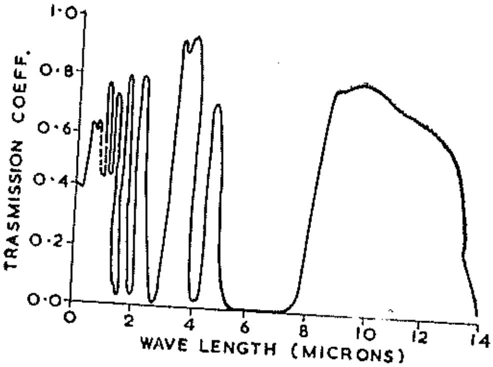

Fig 4—IR transmission spectra of the atmosphere.

UTILIZATION OF THE RESULTS

We have seen that the jet aircraft emits strong IR radiations from its tail pipe. As the propulsion of the craft is due to the exit of the hot gases, the heating of the exhaust cone cannot be avoided. Because of the vast progress of IR technology, these radiations have been used for detection and destruction of aircrafts by IR air-to-air guided missiles.

TABLE 5

TRANSMISSION OF IR IN LIGHT WINDOW REGIONS OF THE SPECTRUM UNDER DIFFERENT CONDITIONS OF WATER VAPOUR AND HAZE[9]

Window wavelength range		Transmission of haze free water vapour				Visual detection ranges V (nautical miles)			
		0·1 mm	1 mm	10 mm	100 mm	2·5	3·3	4·2	5·6
I	0·72–·92	—	—	—	—	—	—	—	—
II	0·92–1·4	—	—	·9	·73	—	—	—	—
III	1·1 –1·4	—	·96	·79	·62	·36	·44	·52	·60
IV	1·4 –1·9	·93	·81	·68	·53	·44	·51	·59	·67
V	1·9 –2·7	·85	·72	·60	·47	·53	·59	·67	·74
VI	2·7 –4·3	·85	·72	·60	·47	—	—	—	—
VII	4·3 –5·9	·92	·71	·51	—	—	—	—	—
VIII	5·9 –14	—	—	—	—	—	—	—	—

On the other hand attempts have also been made in war time to prevent detection and decoy the guided missiles by sending IR flares in the air. The success of this depends on the time of firing of the flares and the power and range of IR radiation output of the flares over that of the aircraft and the ambient surroundings. These, along with a technique for assessment of IR flares, have been discussed in details[10]. An alternative technique for achieving the same purpose is suggested here in the light of the result obtained in the present investigation.

As seen earlier the tail pipe is the hottest portion of the aircraft and is the main source of IR radiations. These radiations can be absorbed by suitable IR absorbing materials. This material can be put in the form of an envelope close to the body of the exhaust cone, if not over the entire body of the aircraft. The IR absorbing material should be

(*i*) light in weight

(*ii*) stable at the extreme temperature developed during all flight conditions

(*iii*) strong absorption spectra in the IR emission range of the jet exhaust and

(*iv*) a poor thermal conductor

Plastic and teflon materials satisfy all these requirements, they are light and exhibit strong IR absorption at 3·5 μ in particular the reinforced plastic[11] are being extensively used in military and space equipment. The glass fibre and ceramic reinforced plastics are widely used in aircraft. Reinforced plastics are employed in the construction of re-entry bodies, space capsules and recovery gear to produce cooling by ablation. These reinforced plastics are thermal insulators.

A vehicle re-entering the earth's atmosphere from a long range ballistic trajectory or a satellite in orbit is subjected to severe aerodynamic heating. In a typical case, the air flowing over the surface attains temperature from 1000 to 7000°C. For survival in this environment, the vehicle must be provided with a heat shield to protect its structure and contents. For the shield itself, use is being made of reinforced plastics and teflon having low thermal conductivity and capable of absorbing large amounts of energy per unit mass through such mechanism as melting, dissociation, ionization, decomposition, vapourisation and radiation (ablation).

Similar analysis is being extended to other air, ground and underwater military targets.

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