THE SPECTROPHOTOMETRIC DETERMINATION OF EXHAUST GAS TEMPERATURES IN THE PULSATING JET ENGINE

A thesis submitted to the Faculty of Graduate Studies and Research at McGill University, in part fulfilment of the requirements for the degree of Doctor of Philosophy.

by

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DEFINITION OF SYMBOLS

h - Planck's Constant, 6.624×10^{-27} erg sec.

k - Boltzman's Constant, 1.377×10^{-16} erg degree^{-1}.

B_λ - Monochromatic spectral brightness of radiation from a small spectral region of width $d\lambda$ in the vicinity of a wave-length λ, this quantity being defined by the equation:

$$dE = B_\lambda \, d\lambda \, dA \, dt \, d\omega \cos\theta$$

where dE is the energy radiated during a time interval, dt, from an area element, dA, of the source within the solid angle element, $d\omega$, at an angle θ to the normal to the surface. Dimension of B_λ are:

$$\text{erg cm.}^{-3} \ \text{sec.}^{-1} \ \text{sterad.}^{-1}$$

a_λ - Spectral absorptivity of radiation in a region of width as above, being the fraction of the incident radiation absorbed by the medium.

$B_{D(F)}$ - Spectral brightness of radiation in a small spectral region 6 Angstrom units wide and just containing the Sodium "D" lines, this radiation being thermally excited in a flame.

$B_{D(B)}$ - Spectral brightness of radiation from a small spectral region 6 Angstrom units wide between the limits 5890 and 5896 Angstrom units, this radiation being thermally excited in a black-body cavity.

$a_{D(F)}$ - Spectral absorptivity of radiation by a flame in a small spectral region 6 Angstrom units wide and just containing the Sodium "D" lines.

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T - Absolute Temperature, degrees Kelvin.

N - Total number of atoms of one particular element present in a thermally radiating system.

N_j - Concentration of those of the above atoms in a specific energy state defined by the energy E_j.

N_i - Concentration of those of the above atoms in a specific energy state defined by the energy, E_i.

ν - Frequency of a spectral line, sec^{-1}.

λ - Wave-length of a spectral line, Angstrom Units (10^{-8} cm.).

$I(\nu)$ - Radiation intensity in Planck's Formula, $\frac{erg}{cm.^2\ sec.\ sterad}$

$\mathcal{J}(\nu)$ - Emission intensity of a spectral line in the Boltzman formula, $\frac{erg}{cm.^3\ sec.}$.

A_j - Transition probability for the j energy state.

A_i - Transition probability for the i energy state.

g_j - Statistical weight of the j energy state.

g_i - Statistical weight of the i energy state.

INTRODUCTION AND SHORT DESCRIPTION OF THE PULSE JET ENGINE

As the pulsating jet engine has been accorded little publicity in any respect apart from its notorious use as a prime mover for the "V-1" type of missile, its mode of operation may be relatively unfamiliar to those well acquainted both with the conventional forms of internal combustion engines and with the more widely employed turbo-jet. Accordingly, there follows a brief description of this engine and its mode of operation.

Basically, the engine consists of a shaped metal tube fitted with one-way flow check valves at the forward or "intake" end. The configuration of the valve bank and the main tube of the engine is illustrated in Fig. 1, the valve bank being at the upper right hand side of the picture. The valve bank, shown as a complete unit in the centre of the figure, incorporates a venturi section wherein the fuel (in this case unleaded gasoline) is normally aspirated into the air stream flowing through the venturi, the rate of fuel injection appropriate to the fuel used being controlled by a small metering valve located in the fuel injector head (Fig. 1 - item 1). The fuel-air mixture passes through the valves consisting of a set of "flapping" blades constructed out of a single sheet of spring steel (Fig. 1-A). Following entry at the valves, the mixture burns in a cylindrical combustion chamber, ignition being provided for the first cycle by means of a small spark-plug located in the wall of the chamber.

Consider the initial cycle of the engine: a combustible mixture of gasoline and air is blown into the combustion chamber by a blast of air from a high-pressure "starting air" supply. Upon ignition by the spark provided by an ordinary type of induction coil, the first explosion occurs in the combustion chamber closing the intake valves and forcing the mass of gas in the long "tail-pipe" section outwards. Inertia effects in the mass flow of this gas result in an over-expansion below atmospheric pressure in the combustion chamber causing a re-opening of the intake valves and the consequent induction of a fresh charge. Ignition of this fresh charge is effected by a back-flow of part of the hot tail-pipe gases towards the combustion chamber. Thus the entire cycle repeats itself at a rate dependant almost entirely on the geometry of the metal tube and proceeds without the benefit of any further spark or of ram air. Existing pulse jets operate in a frequency range of approximately 50 to 270 complete engine cycles per second.

In a comprehensive review of the history of development of this type of jet engine [0], the state of general instrumentation for use in the study of the device as of the late summer of 1946 is summarized as follows: "Measurement techniques for pulsating jets were necessarily the subject of development as well as application. Satisfactory techniques for measuring the time average of thrust, fuel flow, air flow and body temperature were established after minor modifications of existing methods. Work was commenced to develop techniques for observing instantaneous effects, including wall static pressure, wall static temperature, and flame and air velocities internally and near the entry and exit. Attempts were made to apply various mechanical, electrical and optical measuring devices to this engine. In most cases, application of existing techniques required the extension of the useful ranges. For instance, pressure pick-ups in common use fell far short of the demands of this engine particularly with regard to cooling for high rates of heat transfer. A second example was in the hot wire anemometry for instantaneous velocity measurements; existing equipment failed at lower velocities and temperatures than those encountered in pulse jet operation even under static conditions. Broadening of the applicability of these instruments to include this engine was a slow and difficult process, and advancements were modest at best".

Great impetus was given to the development of adequate instrumentation not only by the pressing requirement for such devices in the development of these engines but also by the need for actual numerical values of pressure, temperature, gas density and gas velocity for substitution in the theoretically derived hydro-thermodynamical equations which had been developed by MacDonald and his school (1) in their one-dimensionalized theoretical treatment of the pulse jet.

At this time, therefore, among the other instrumentation requirements, it became of fundamental importance to develop some method of determining and recording the rapid cyclic temperature variations at points in the main combustion chamber, the transition cone, the tail-pipe and finally in the exhaust gas flame. The problem was assigned to the author (then engaged as a Research Associate of New York University) by Professor MacDonald, Technical Director of a United States Navy-sponsored Jet Propulsion Project in that University. Reduced to its simplest terms, the problem was as follows: "It was required to design and construct an instrument capable of providing an accurate record of the oscillating gas temperatures at any given point in an operating pulse jet motor. The instrument was required to record temperature variations at a fundamental frequency of two hundred and fifty (250) cycles per second or less, and was to be fully responsive to harmonic frequency components up to the limit of 2500 cycles per second. The instrument was not to be subject to radiation or other losses or to any form of destructive action by the hot gases of the jet. Finally, the insertion of any part of the instrument (if insertion was necessary) into the hot gases was not to lead to any additional perturbation of their existing mode of flow".

Information received from the Navy Research Station at Annapolis clearly specified that the flames in all parts of the pulse jets tested there were non-luminous (as opposed to the luminous, soot-containing types of flame). The instrument requirements were thus at first limited to a device capable of meeting the above specifications for a colourless flame. It was not until the construction and testing of a glass-walled pulse jet had finally been accomplished at New York that the flames both in the combustion chamber and in the tail-pipe were revealed to be brightly luminous, the exhaust flame only being non-luminous (a faint bluish flame). At this point, the research diverged, a group at New York commenced investigation of methods for temperature determinations for luminous flames while the author, having at this time returned to McGill, continued the original research as applied to the non-luminous exhaust flames.

A thorough survey of the literature in the field of gas temperature measurements was made both by MacDonald and, independantly, by the author in the hope of finding either an existing method of dealing with the problem or, at least, one which could be conveniently modified so to do. Of the mass of literature on the subject, dating from 1890 onwards, only one article [(2)] gave promise of a method which might be employed with considerable modification to meet the requirements stated above. An outline of this survey and a discussion of the above mentioned pertinent article will now be given.

The very earliest methods of temperature determination applicable strictly to non-luminous flames consisted of the introduction of thermocouples into the body of the flame; many elaborate techniques were evolved to compensate for losses due both to radiation from the couple and to conduction along the leads. Such experimental methods are described by Waggener[3], by Burkenbusch[4] and by Nicols[5]. It was realized that all thermocouple methods must be ruled out, insofar as the present problem was concerned, due to the time lag associated with the thermal capacity of any practical thermocouple element even if satisfactory compensation could be effected for radiation losses. This time lag, of no concern in static flame temperature measurements, constitutes the limiting factor when the recording of rapid temperature variations is contemplated.

The first optical method used for flame temperature measurement was applied by Kurlbaum[6] to the luminous, carbonaceous type of flame but served as the basis for the method of spectral line reversal first employed by Fery[7] and, independantly, by Kurlbaum and Schulze[8]. This procedure, which has since been used with success by Griffiths and Awbery[9] and by Loomis and Perrot[10][11], in their determinations of static flame temperatures, merits some discussion in detail, the use of the method being at one time contemplated for the calibration of the apparatus finally developed in this research.

The spectral line-reversal method depends essentially on the visual matching of two spectral brightnesses. Consider a black-body radiator placed behind a flame coloured, for example, with sodium: this element emits the characteristic resonance doublet at 5890 and 5896 Angstrom units in the yellow region of the spectrum (the familiar "D" lines). Let a spectroscope be sighted through the flame onto the black-body: if the black-body is at a lower temperature than the flame, the observer will see the "D" lines appear bright against the background continuous spectrum due to the black-body. On the other hand, if the black-body be at a higher temperature than the flame, the "D" lines will appear dark by contrast against the continuous spectrum. There will obviously be some one temperature of the black-body at which its spectral brightness in the region of the "D" lines equals the brightness of the light transmitted through the flame plus the brightness of the "D" line radiation originating in the flame itself. Hence, at this particular temperature, the observer sees only a continuous spectrum without either a superimposed bright or dark pair of lines. Assuming that the black-body temperature has been finely adjusted to give this condition, the following equation may be written:

$$B_{D(F)} + B_{D(B)}\left(1 - a_{D(F)}\right) = B_{D(B)} .$$

where the symbols used have been previously defined. This equation reduces to:

$$\frac{B_{D(F)}}{B_{D(B)}} = a_{D(F)} .$$

This latter equation is of the form of Kirchhoff's Law which applies strictly to thermal radiation and, as we have abundant evidence [12] that this law applies to the emission and absorption of resonance radiation of the alkali metal carried in the flame, the temperature of the flame is seen to be identical with that of the black-body when reversal of the spectral lines has been obtained.

The line reversal technique as applied by the above investigators has lead to accurate and consistent results for temperatures at specified points in steadily burning flames. It is, however, obviously a static method, insofar as it requires the visual matching of brightness, and hence is completely unsuited to the determination of rapidly varying temperatures such as those encountered in the present problem. It is noteworthy, however, that the method has been extended to the case of colourless flames in the Otto Cycle Engine by the use of a stroboscopic arrangement whereby the brightness matching is effected only at a specified point in the cycle of the engine. This is achieved by the use of a stroboscopic disc driven synchronously from the engine crank-shaft, a set of holes cut into the disc allowing the light from the comparison radiator to pass through the flame during a very short time interval at some specific point of the engine cycle. Procedures devised for this point-to-point temperature measurement are described by Hershey and Patton (13), by Watts and Lloyd Evans (14), by Rassweiler and Withrow (15) and by Brevoort (16). The method is inapplicable in the case of the pulse jet due to the fact that not only are the cycles of the engine not strictly repetitive but there is no moving part with which to effect the synchronization of a stroboscopic disc. Reference will be made later to the attempted use of the simple line-reversal method as a means of static calibration of the recording spectrophotometer.

A further optical method of temperature measurement in the case of non-luminous flames depends upon the determination of emission and absorption of radiation by the flame in the infra-red region of the spectrum between the limits of 2 and 6 microns, and was extensively investigated by Schmidt (18) for the particular case of the non-luminous Bunsen flame. Schmidt was able to prove conclusively that the Planck Radiation Law applied to the radiation of certain molecular bands in this region. In order to apply this method to the non-luminous flames in the exhaust of the pulse jet, it would first be necessary to examine the complete infra-red spectrum from a gasoline-air flame in the hope of finding some band radiation to which the above law applied. Facilities for such a study were not available. Inertia-less detection of such radiation from the flame would further require the use of some special type of photo-electric cell; application of the method would undoubtedly necessitate the careful control of the concentration of water-vapour and carbon-dioxide in the atmosphere surrounding the jet engine -- a matter of no small difficulty. No attempt was, therefore, made to explore the applicability of the method any further.

The procedure finally adopted was suggested by MacDonald following a consideration of an original report due to Graff[2] in which a description was given of a radiation method of flame temperature measurement applicable to the flames in the Otto Cycle Engine. Graff concluded that, as the radiation properties of the intermediate and final combustion products in the combustion chamber of this type of engine were not sufficiently well defined and were, in part, unknown, it would be feasible to attempt to make exact temperature measurements by means of the radiation due to certain additive substances purposely introduced into the combustion chamber. Suitable additives were found to be the alkali metals introduced with the fuel in the form of organic salts soluble in gasoline. Graff quotes some preliminary investigations of Yosida (a reference which has not, as yet, been located) wherein it was shown that the above additives (when present in sufficient concentration in the flame) emit, within the limits of their resonance lines, a radiation whose intensity is a function of temperature only, as given by the Planck formula: this is to say that monochromatic black-body conditions are established in the flame at the particular wave-lengths of the resonance lines employed. It is at once apparent, however, that, in general, this condition is not attained, the radiation intensity due to the additive depending not only upon the temperature but also upon the concentration of the additive in the particular portion of the flame examined. The report is confusing in that two contradictory statements are made:

(1) that the radiation intensity depends only upon the temperature according to Planck's Law for black-body radiation, if the wave-length of the resonance line is substituted for the wave-length in the formula, and (2) that the radiation depends upon the ratio of additive to fuel. Furthermore, Graff makes no mention of any investigations pertaining to the minimum amount of additive required to effect black-body conditions in the flames which he examined.

The apparatus used in the application of the above method to the Otto Cycle Engine consisted of a photoelectric cell used as the radiation detector, an amplifier to amplify the voltage output of the cell to the level required for the operation of a cathode ray oscilloscope on the screen of which the intensity versus time record was presented. A colour filter placed in front of the cell effectively screened the detector from any band or continuous radiation from the flame. No mention is made either of the calibrating procedure employed or of the means of recording the deflection of the cathode ray oscilloscope beam.

To apply the method to the case of the pulse jet exhaust, it was first necessary to examine whether or not the concentration of the additive which it would be possible to inject into this engine could be increased beyond the minimum level required to provide monochromatic black-body conditions in the flame. Before such a study could be undertaken, some simple form of photometric detector, an amplifier and some form of indicator, had to be designed. Accordingly, the design and construction of these units was begun as will be described hereafter in detail, and a method sought whereby the necessary concentration of additive could be injected into the engine.

ANALYSIS OF THE PROBLEM

While it is not intended to enter here into an abstract discussion of the concept of temperature, nevertheless it is important to consider briefly the historical development of the concept and, in particular, to note some of the means whereby the intensive physical quantity, temperature, may be given adequate definition.

The concept of temperature has its original basis in physiological sensation: the terms "cool", "lukewarm", and "red-hot" are commonly employed to describe the thermal states of objects, indicating that we possess some qualitative appreciation of temperature. Following the statement of the Law of Conservation of Energy by Helmholtz in 1847, the concept of temperature became associated with the flow of heat from one body to another by the thermal processes of convection, conduction and radiation: thus, we have the classical definition of temperature stated by Maxwell in his "Theory of Heat" -- "The temperature of a body is its thermal state considered with reference to its power of communicating heat to other bodies". This definition of temperature is completely adequate provided we limit ourselves to a macroscopic point of view with regard to thermodynamical phenomena. It is, however, frequently advantageous to adopt the microscopic viewpoint using the methods of statistical mechanics: this latter viewpoint is especially suited to a discussion of the present problem.

The study of statistical mechanics associates the quantity temperature with a state of statistical equilibrium; a particular distribution of the total energy among the components of a thermodynamic system is regarded as defining a temperature. These components may be atoms or molecules of a gas, in which case the statistics of Maxwell and Boltzmann are applicable to a discussion of the system. On the other hand, the components may be electrons forming an electron gas in which case the statistics of Ferni and Dirac must be employed. Insofar as the quantity temperature is defined by a state of statistical equilibrium, it can only be accurately assigned to a system in which such an equilibrium exists. Theoretically, then, the concept of temperature as applied to the particular case of the completely or partially burned gases comprising a flame corresponds to the following postulated state of complete statistical equilibrium in these gases. Collisions between the atoms or molecules and interaction with the radiation of the system, although continually changing the energy state of every individual particle, maintain, on the average, the randomness of direction of motion and the constancy of (a) the percentage of molecules or atoms possessing a specified velocity, (b) the percentage of molecules or atoms possessing a given quantum state of rotation, of vibration and of electronic excitation, and, finally, (c) the concentration of the dissociation products. It is entirely possible, in many cases, to calculate the theoretical temperature for such a system and for a specified energy content using heat capacities and dissociation equilibria obtained from band spectroscopic and other data by the methods of statistical mechanics.

It is here assumed, following Lewis[19], that the equilibrium (a) is established to a close approximation in all zones of a flame due to the rapidity of the molecular collision sequences. It remains, however, an open question whether the equilibria described under (b) and (c) are also attained to a sufficient extent to allow an experimentally obtained temperature corresponding to the equilibrium (a) to be taken, with negligible error, for the temperature of the system. Hence, if it is desired to obtain the theoretical temperature of a particular system, the establishment of the equilibria (b) and (c) will have to be thoroughly investigated.

A further complicating factor arises out of the experimental procedure employed in this research where sodium chloride dust is added to the exhaust gases. An additional state of thermal equilibrium must be considered, namely the constancy of the percentage of atoms of the additive possessing a given degree of electronic excitation. In this connection, it has been shown by Bauer(20) and also by Awbery and Griffiths(9) that identical experimental temperatures are obtained in the case of a flame by means of the line reversal technique using several of the alkali metals as additives. This experimental fact admits no other interpretation than that a complete thermal equilibrium exists between the translational degrees of freedom of the gas molecules and the electronic degrees of freedom of the alkali metal atoms. Hence, noting that the intensity of radiation from the atoms of the additive is intimately connected with the numbers of those atoms in the several excited states (the several electronic degrees of freedom), it is possible to associate a measured radiation intensity with a specific temperature as defined below.

In the case of the jet exhaust gases considered here, the temperatures determined are, therefore, defined to correspond to states of complete statistical equilibrium between the molecules of the exhaust gases and the electronic degrees of freedom of the additive sodium atoms. No attempt will be made to investigate the establishment of the equilibria (b) and (c): such an attempt would be unnecessary insofar as any modern gas dynamical calculations as applied to jet engines include the simplifying assumption that the gases may be regarded as "perfect". Hence, only a temperature corresponding to statistical equilibrium in the translational degrees of freedom is of useful significance in such calculations.

Three distinct methods have been employed by previous investigators to effect the injection of the additive into the flame: (i) the additive is injected in the form of a spray of water solution of an alkali salt (ii) the alkali is injected in the form of powdered dust of such a salt and (iii) a small solid bead of fused salt is inserted into the body of the flame on the end of a refractory wire. In all of the above cases, examination of the radiation from the coloured flame by means of a spectroscope reveals the line spectrum of the particular alkali metal used: a line spectrum as opposed to a molecular band radiation or the continuous spectrum emitted by incandescent solid particles. Thus the radiation is seen to be due to free atoms of the alkali metal in the flame. No consideration has apparently been given by previous investigators to the mechanism of production of these free atoms in the body of the flame. It is believed that these atoms originate in two ways (a) the solid salt sublimes giving off a small amount of salt vapour which dissociates into the metal and the acid ions; (b) the salt melts, vapourization of the molten salt occurs and dissociation of the vapour phase occurs as above. It is considered extremely unlikely that any appreciable dissociation of the salt occurs in either the solid or liquid phases. Of the two processes quoted above, that consisting of direct sublimation of the salt followed by dissociation of the vapour is considered more likely. Mellor[25] states that the lithium, potassium and sodium chlorides begin to sublime at their respective melting points; thus, in the case of sodium chloride used in this investigation, sublimation begins at approximately 800 degrees Centigrade, a temperature well within the range of those encountered in the jet engine exhaust. In the case of aqueous injection, evaporation of the water is achieved rapidly in the flame, the ions of the solution combining to form small aggregates of sodium chloride crystals. Such small aggregates of crystals are, of course, directly provided in the flame if the dust injection technique is employed. By use of the latter method, pronounced cooling of the flame due to the absorption of heat of vapourization by the water is eliminated.

The nature of the intensity-temperature relationship for the additive injected into the hot flame gases has already been seen to alter with the concentration of the additive. Two limiting cases may be distinguished to which the terms "Planck Radiation" and Boltzman Radiation" have been applied by Smit[21]. Thus consider a perfect black-body cavity, the walls of which are maintained at a uniform temperature T: let some means be provided whereby a controlled amount of some additive, sodium for example, can be admitted in the form of a gas. If now two small holes are bored axially into the cavity as shown in Fig. 2-A, it will be observed that the radiation emerging from the wall (direction 1 in the figure) will obey the Planck formula,

$$I(\nu) = \frac{2h\nu^3}{c^2} \cdot \frac{1}{(e^{h\nu/kT} - 1)},$$

whereas the radiation observed in the axial direction joining the two holes will give the line spectrum of the sodium gas, the intensities of the spectral lines of the gas depending upon the populations of the energy levels according to the Boltzmann formula,

$$\mathcal{J}(\nu) = h\nu \, . \, A \, . \, g/Z \cdot e^{-E/kT} \, .$$

This situation is represented in Fig. 2-B where the nearly horizontal line represents the spectral distribution of the energy in the radiation coming from the wall while the lower curve represents the energy distribution in the line spectrum observed along the axis. As the concentration of the additive is increased so will the intensities of the lines increase being finally limited by self-absorption to the "ceiling" represented by the Planck curve. Thus, when this condition is attained, monochromatic black-body conditions will have been established in the cavity for the axial direction of observation for each of the spectral lines. It is to be particularly noted that, in the absence of self-absorption, the spectral lines would extend much higher as shown by the dotted curves and would not be hindered by the ceiling.

A simple experiment shows that monochromatic black-body conditions can likewise be established in the particular case of the "D" line resonance radiation of sodium when the latter element is thermally excited in a flame. This fact was verified by the author in a preliminary experiment at New York which may be briefly described as follows: a saturated solution of common salt was aspirated under some 25 pounds air pressure into a rectangular Bunsen type burner together with ordinary coal gas used as fuel. A photoelectric cell used as a radiation detector received radiation from a one centimeter square area of the flame at the front of the burner. Once steady burning of the flame had been established, an opaque barrier consisting of a thin sheet of Transite was moved into several positions along the length of the burner effectively reducing the thickness of the flame seen by the detector as it moved towards the front of the burner. A plot of the radiation intensity against the distance of the barrier from the front of the burner is illustrated in Fig. 3. From this result the conclusion is drawn that monochromatic black-body conditions were established in one centimeter thickness of the flame, the requisite amount of additive being obtained by injection of the saturated salt solution. Theoretically, the above conditions could be established in a flame of lesser thickness but, in practice, it would be impossible to inject the necessary amount of additive.

It is then to be determined whether the black-body condition can be established in the exhaust flame of a pulse jet, this flame having in the present case a thickness of 4.14 cms. at the extreme end of the tail-pipe. If this condition can be shown to exist, the intensity of the "D" line radiation will follow the Planck Law and the calibration of the photometer in terms of radiation intensity against temperature may be achieved by simply sighting the instrument on a black-body cavity, the temperature of which may be set at appropriate values by control of the heating of the cavity. The black-body temperature of the cavity may be determined with the aid of a conventional disappearing filament optical pyrometer, factory-calibrated to give accurate temperatures for bodies under black-body conditions.

DESCRIPTION OF THE APPARATUS

The original apparatus and experimental arrangements used in the investigation of this problem at New York University is illustrated in Figs. 3-A to 5-B. As a complete description of much of this has already been given elsewhere[22], only an occasional reference will be made here in order to show the development both of the type of apparatus and the techniques used from the time of the initiation of the project at New York University to its final completion at McGill.

The apparatus is most conveniently discussed using the following sub-division:-

(a) The method of injection of the Sodium additive.

(b) The type of radiation detector used together with its associated optical filtering arrangements.

(c) The type of amplification of the detector signal employed.

(d) Nature of the tests to establish the existence of monochromatic black-body conditions in the flame.

(e) The method of calibration of the spectrophotometer.

(f) The method of recording of the temperature variations.

Sub-division (a). Identical additive injection arrangements were used both in the initial and final forms of the experiment, the Sodium being injected through the intake valves of the jet in the form of a finely powdered inorganic salt using a small blower located some distance away from the valve bank. This method was considered superior to a water-spray type of injection technique originally used for the same purpose by some earlier investigators at the Aerojet Company in California and described in a confidential report issued by that organization. It is considered that there is less probability of the operation of the engine being adversely affected by the addition of a dry powder than by the considerable amount of water required to affect adequate aqueous injection of the additive. The cooling of the flames due to the absorption of the heat of vapourization of water has previously been discussed.

Sub-division (b). The radiation detector, a simple form of spectrophotometer, is shown in its operating position in Fig. 7. The arrangement of the optical components is given in Fig. 6-A and the electrical circuit given in Fig. 6-B. An image of unity magnification of the source (a small hole pierced into the blast and radiation screen -- diameter 13/64 inch) is formed by an auxiliary bi-convex lens on the spectrometer slit. The light from this image is collimated by the bi-convex lens L-1, the prism P being completely flooded with parallel light rays. The prism having been set in the position of minimum deviation for the "D" line image, this image is formed by lens L-2 at the knife-edge jaws of a second adjustable slit, A-2. This latter slit is adjusted until the bright image of the "D" lines just disappears through it, the light in this spectral region being received by the lens L-3 whose focal plane is at the second slit. Finally the light emerges as a parallel beam to uniformly flood the photo-cathode of the detector, a standard electron-multiplier photo-cell (R.C.A. Type 931-A). This tube obtains the requisite voltages for its several dynodes and cathode from a potentiometer, R-1 to R-11, the resistor chain being supplied at E with 2000 $\pm$ 1 volts D.C. from a series triode type electron-regulated power supply. As the power supply used is of the type normally employed to supply the regulated voltages for the control elements in an ultra-high frequency Klystron oscillator, the regulation and low "ripple" content has proven more than adequate to meet the needs of the present application. As the electrical circuit of the power supply is entirely conventional, no further details are deemed necessary here. The voltages furnished to the dynodes and cathode are those recommended in the R.C.A. Tube Handbook for this particular tube and are tabulated below.

TABLE 1

Dynodes 1 to 8	-	100 volts per stage
Dynode 9 to anode	-	50 volts
Cathode		950 volts

While the instrument is normally operated with the switch S-1 in the position shown, the same switch can be set to the dotted position and a 0 to 100 micro-ampere meter thereby included in the circuit between the anode and load resistor, R-12. This feature provides for routine adjustment of the instrument and also would enable the use of this device for the measurement of static temperatures in terms of tube current. The entire spectrophotometer is contained in a light-tight metal box, this latter also protecting the detector from the considerable blast from the jet. To further protect the unit from vibration, the spectrophotometer is mounted on a separate heavy table from the engine. Levelling screws are shown in the positions B.

As it was imperative to check both the filtering efficiency of the optical arrangements and also the linearity of the photo-cell prior to use of the instrument, a broad filament type of tungsten lamp was placed in the position of the normal source and a series of readings taken of the tube current (switch S-1 in the dotted position) for a measured set of lamp currents. The particular lamp employed had previously been calibrated in another experiment and the relation between its apparent black-body temperature and current were known. The relation Logarithm to the base "e" of the intensity (as measured by terms of the photo-current) against the reciprocal of the absolute temperature of the lamp is given in Fig. 11. Provided the filtering were adequate and the tube response linear, this curve should satisfy the Wien Law equation:

$$\mathrm{Log}_e\, I \;=\; \mathrm{Log}_e C_1 \;-\; \frac{h}{k} \cdot \frac{1}{T}$$

Using a "mean wave-length" of 5893 Angstrom units and the accepted values of h and k, the theoretical slope of the line was calculated: this gave the figure -2.48. The actual measured value of the slope is -2.57, this leading to an error of just under 4%. Considering the roughness of the measurements, the above relative agreement was taken to confirm a sufficient filtering of the radiation incident on the instrument and a satisfactory linearity of the cell.

The spectrophotometer thus described replaced a much simpler form of filter photometer used as the radiation detector in the earlier work. The Wratten type filter, used in the original instrument was deemed to be not sufficiently selective for the present application. The original unit is shown in its operating position at the upper left hand side of Fig. 3-A. It is described in detail in (22).

Sub-division (c). As it was necessary to provide uniform amplification of the output signal of the photo-cell over the range 0 to 2500 cycles per second, two alternate means of achieving this requirement were presented (1) to use a stable direct-coupled (D-C) amplifier or (2) to employ the conventional technique of 100% square-wave modulation of the signal prior to amplification in an ordinary resistance-capacity-coupled amplifier capable of passing, without distortion, the modulating "square wave" itself. No satisfactory D-C amplifier being available, a search of the literature revealed only one particular type which promised any measure of success. This utilizes a circuit quoted in (23) and has been employed in a standard type of Cathode Ray Oscilloscope Outfit (R.C.A.'s Model 327-A). Using the data furnished in the above reference, an amplifier of this type was constructed: upon testing the device, great difficulty was experienced with the alignment as three separate and distinct bridge-balances had to be effected; furthermore, the amplifier proved to be incapable of working into a resistive input of the order of magnitude of the photo-cell load resistor. After a considerable expenditure of time, the investigation of this amplifier was abandoned and the modulation-A.C. amplifier system considered.

A confidential report which became available at this time described a method of square-wave modulation of voltage signals by use of an electronic "D-C to A.C. Inverter". Square-wave modulation of the signal was reputed to be effected by this device at the rate of 10 Kilocycles. This unit, one of which was constructed and tested at New York, possessed two major disadvantages: the rate of modulation of the signal was shown to be too low for an adequate preservation of the form of the voltage output of the cell and, furthermore, the extreme sensitivity of the device to minute changes of filament voltage lead to insuperable difficulties in practice. Attempts were made both to overcome the difficulty of accurate adjustment of the filament voltages to provide adequate operation of the unit and also to extend the modulation rate to 100 Kilocycles per second. Bridge balancing difficulties, already found to be difficult at 10 Kilocycles, proved insurmountable at 100 Kilocycles. Discussions with the original designer failed to elicit a satisfactory method of filament voltage adjustment. Finally, investigation of the device was discontinued.

With the above experiences in mind, the design of the system of amplification at McGill was attempted as follows. Instead of effecting electronic modulation of the voltage signal from the cell, it was proposed to modulate the intensity of the light incident upon the cell by the interpositioning of a rotating toothed wheel between the radiation source and the photometer. Mechanical limitations limited the material of the disc to aluminium and its maximum rate of rotation to 20,000 revolutions per minute. Using 55 square holes milled into the peryphery of the disc, a modulation rate of approximately 20,000 cycles per second was finally obtained in practice. A picture of the disc, together with the mechanical tachometer used to measure its speed of rotation, appears in Fig. 8; the general arrangement of the apparatus is shown in Fig. 7-A while the details of the lens system, the protecting housing of the interrupter disc and its high-speed driving motor is shown in Fig. 7-B. Apart from occasional slipping of the belt drive from the motor to the drive shaft, this arrangement gave trouble-free service throughout its period of use, the intensity against time wave-forms agreeing to a notable extent with those obtained using the final amplification system. The A.C. amplifier of a Dumont Type 208 Oscilloscope having a frequency coverage of 2 to 100,000 cycles per second was used in conjunction with the interrupter disc. A typical wave-form obtained with this interrupter-A.C. amplifier combination is shown in Fig. 22. Insuperable difficulties were, however, encountered when an attempt was made to calibrate the apparatus, a limitation which will be discussed in detail below.

In the final arrangement, adequate amplification of the photo-cell signal up to the necessary level required to operate the oscilloscope beam was achieved by increasing the light level into the cell, by effecting the major portion of the amplification in the cell itself and by following this up with a single stage of "push-pull" D-C amplification. By increasing the light level to the photo-cell and by use of a 200,000 ohm load resistor in the anode circuit, it was found possible to obtain a voltage signal adequate to operate the D-C amplifier used as a fourth amplifier stage in the above oscilloscope outfit. This amplifier is a single stage "push-pull" type having a frequency range of 0 to 100,000 cycles and has its output directly connected to the deflection plates of the cathode ray tube. Tests over a considerable period of time have demonstrated the excellent stability of this single D-C stage and have shown the operation of the complete final system to be adequate in all respects.

Sub-division (d). The procedure for determining the existence of monochromatic black-body conditions in the case of a static, steadily-burning flame has already been discussed: insofar as this method involves the insertion of an opaque barrier into the flame, it is immediately obvious that the technique is inapplicable to the jet exhaust flame -- nothing must be inserted into the latter which would disturb the mode of flow of the gases. As it was imperative to devise some form of test for black-body conditions in this case, it was decided to assume the applicability of the Kirchhoff Law for the "D" line radiation and to test the flame for unity monochromatic absorptivity: this test was effected as follows. Radiation from a small area of the flame diammetrically opposite from the source-hole in the radiation screen was received by a small plane mirror and reflected back into the flame towards the spectrophotometer. If the flame possessed unity absorptivity for the "D" line radiation, it was considered that identical radiation intensities would be recorded by the photometer whether the mirror was exposed to radiation from the flame or effectively cut off from the radiation. In a preliminary experiment designed to test the applicability of the method, the jet flame was simulated by the flame of a standard "Fisher" burner into the air-supply of which a considerable quantity of sodium was injected in the form of powdered sodium chloride. Using this arrangement, the intensity recorded with the mirror exposed exceeded that obtained with the mirror screened from the radiation by a factor of 25%, thus indicating that the monochromatic absorptivity of the flame was far from unity.

In the application of this method to the engine exhaust flame, it was decided to provide a satisfactory basis for the comparison of intensity both with the mirror exposed and with the latter screened in the following manner. A rotating metal disc having four open sectors symmetrically cut into it was arranged to spin in front of the mirror thereby exposing and screening the latter during alternate sets of four jet cycles. It was, thereby, anticipated that all cycles would show approximately the same maximum amplitude and general configuration in the case of unity absorptivity while alternate sets of four cycles would show marked differences if the monochromatic black-body condition were not established. When the results of test runs on the engine failed to reveal such alternate sets of four cycles (the variations both in maximum amplitude and general form varying in a perfectly random fashion from cycle to cycle), it became necessary to indicate on the intensity-time record itself the precise interval during which the mirror was screened and exposed. This was achieved by fitting a cam to the driving shaft of the four-sector disc, this cam being arranged to close a sensitive micro-switch whenever a segment of the disc completely screened the mirror. The switch itself was connected in series with the "External Contactor" terminals of a General Radio "Strobotac" which provided a brilliant flash of light each time complete screening of the mirror was accomplished. These light flashes fell on the face of the cathode ray oscilloscope and were recorded by the camera simultaneously with the deflection of the beam. The four-sector disc, the driving motor (operated at 3150 revolutions per minute) and the plane mirror is fully illustrated in Fig. 8-B.

Sub-division (e). Calibration of the spectrophotometer would have been most conveniently effected by the use of a standardized tungsten lamp for which the relation between the apparent black-body temperature of the filament for radiation in the "D" line region and the filament heating current had been accurately determined. The accurate calibration of such a lamp is a matter of considerable practical difficulty and necessitates the use of specialized optical apparatus; furthermore, the cost of such a calibrated lamp as supplied on special order by the General Electric Company was regarded as prohibitive. The obvious alternative of constructing some form of black-body cavity, the thermal radiation of which would be absolutely independent of the emissivity of the material of the cavity, was initially thought to involve to many practical difficulties in the early stages of this research at New York.

It was suggested that calibration of the photometer could be effected in terms of the radiation from small areas of static flames of different temperatures in which monochromatic black-body conditions at the "D" line wave-length were known to be established. The temperature of the particular flame used could be obtained by the line-reversal technique: the apparatus would be calibrated in terms of deflection of the oscilloscope beam against temperature of the radiation source obtained in this manner.

An experimental arrangement designed to utilize the above procedure was initially set up at New York University: the several units are illustrated in Figs. 3-A, 3-B and 4-A. A small aperture placed immediately in front of the flame of a large Bunsen burner served as the radiation source. The large rectangular secion burner, shown in the centre of the above pictures, could be supplied with the following fuels: (1) house gas, (2) propane and (3) ethylene, in order to provide radiation sources of different temperatures. Air, supplied under pressure from a small diaphragm type pump, was introduced into the burner via an aspirator in order to provide aqueous injection of the additive from a saturated solution of sodium chloride. To obtain very high flame temperatures, another form of burner was constructed from a conventional welding torch: this arrangement made possible the use of an air-acetylene mixture. While it was found practically possible to obtain a one-centimeter thick flame in which the requisite black-body condition was established, using the first three fuels in the large, rectangular burner the order of temperature differences realized was only some twenty degrees Centigrade. This very limited source temperature range was completely unsatisfactory. On the other hand, in the case of the acetylene-air flame, no method was ever found whereby the requisite amount of additive could be injected into the flame. The entire method of calibration was soon abandoned.

The method of calibration finally adopted employs a cylindrical black-body cavity heated electrically to incandescence by a concentric graphite resistor. The complete unit is illustrated in the drawing of Fig. 9-A and its associated electrical circuit in Fig. 9-B. A photograph of the complete unit appears in Fig. 10. With reference to Fig. 9-A, the black-body cavity itself consists of a Zirconium Oxide (ZiO_2) (this refractory material having a melting point in the vicinity of 2500 degrees Centigrade). Both the aperture and the rear wall of the cavity were core-drilled out of a block of solid Zirconium Oxide. The concentric graphite heating element was made from a commercial grade graphite electrode of the type commonly used in metallurgy: the life of this element was extremely short, a new tube being required after every second operation of the furnace. This graphite resistor was tightly fitted into massive cylindrical carbon end-blocks which served both to effect a uniform distribution of the heating current and as a satisfactory mechanical support for the graphite tube. The end-blocks fitted tightly into circular holes cut into sections of one-quarter inch Transite sheet: the latter also held in position a section of five inch diameter steel pipe approximately four inches long. Between this pipe and the graphite electrode a sufficient quantity of very light powdered Magnesium Oxide was packed to provide adequate heat insulation and also to inhibit the burning of the graphite in the atmospheric oxygen.

The heating current, controlled in magnitude by a variable transformer in parallel with the 110 volt, 60 ampere mains supply, was obtained from a high-current transformer having a zero to fifty ampere meter incorporated in its primary circuit. The necessary cooling of the heavy copper concentric electrodes surrounding the end-pieces was adequately effected in practice by circulating ordinary tap-water through one-quarter inch copper tubing brazed to the outer surfaces of both electrodes.

A central pivot arrangement together with the provision of flexible leads allowed the entire furnace to be swung from one fixed position through an angle of 30 degrees into another. Thus, by moving the furnace from one position to the other, the cavity could be viewed as required by either the spectrophotometer or by a Leeds and Northrup disappearing filament optical pyrometer (type 8622). As soon as the radiation intensity from the cavity was recorded by the photometer, the furnace could be rapidly moved into the second position where the cavity temperature could be recorded by the pyrometer.

The circular aperture of the cavity was chosen to be identical in area with the source-hole in the blast screen, hence the images formed on the spectrophotometer slit both from the flame itself and from the cavity aperture were of equal size. It is fully realized that perfect black-body conditions were not fulfilled in the cavity due both to non-uniform electrical heating and to the extremely poor thermal conductivity of the Zirconium Oxide which introduced large temperature gradients in the cavity walls. In the absence of a tungsten cavity, however, this material was the only available refractory having a sufficiently high melting point. It is, therefore, considered that the best possible approximation to black-body conditions was effected using available materials. Apart from the necessity for frequent replacement of the heating element, the entire unit gave trouble-free operation throughout its period of use.

Sub-division (f). The recording of the intensity-time variations has been effected throughout the entire period of research by the use of the conventional cathode ray oscilloscope-continuous film camera combination, the output signal of the amplifier being presented in the form of an "X"-deflection of the electron beam. Initially, a Dumont Type 241 Oscilloscope outfit was employed whereas later a Dumont Type 208-B outfit was used due to the excellent suitability of the D-C amplifier incorporated as a fourth amplifier stage in this oscilloscope. Both oscilloscope types were fitted with cathode ray tubes having a P-11 screen for optimum photographic results. The high-speed, continuous film camera used was a General Radio Type 651-A-E (incorporating an f-1.5 lens) in which the film (Eastman Super XX) travelled in a direction perpendicular to the X-axis of the oscilloscope at the maximum speed of 25 feet per second. Eastman Kodak "D-11" developer and an ordinary acid fixer and hardener were employed for film processing which was effected in a Morse developing tank. Timing marks were impressed on the film as required by utilizing the flashes of the Strobotac previously mentioned. Excellent photographic results were at all times obtained with the above arrangements as fully illustrated in the quality of the records as typified by Figs. 15, 16, 17, 18 etc.

OPERATION OF THE APPARATUS

A period of approximately one-half hour was reserved in order to allow the electrical circuits of both the oscilloscope outfit and the regulated high-voltage power supply to become sufficiently stabilized. Both units were accordingly switched on at the start of the interval, the requisite adjustments were made of the "Intensity" and "Focus" controls of the oscilloscope and the output of the power supply regulated to 2000 volts D-C using a standard Simpson test-set operating on the 5000 volt range. The best photographic results were obtained with the "Intensity" control of the oscilloscope at its maximum setting and with the "Focus" control adjusted to give the minimum spot size (minimum beam width) consistent with the intensity setting. Having completed these adjustments, the "Beam Switch" of the oscilloscope and the high-voltage switch of the power supply were opened until shortly before the initiation of the particular test run on the engine.

During the above preliminary interval, the camera was loaded with approximately fifty feet of film, the A.C. mainsvoltage was checked and recorded, the alignment of both the auxiliary lenses and the main optical system of the spectrophotometer was carefully examined and the additive injection blower loaded with finely powdered sodium chloride dust and set in position. Finally the jet engine itself was accurately placed in position with the end of its tail-pipe just clear of the source-hole in the blast screen and securely clamped to the heavy supporting table.

Due to the extreme sensitivity of the multiplier photo-cell, all the engine tests were effected with the room in complete darkness apart from the small flashing light of the Strobotac. As soon as the room was darkened, the high-voltage supply to the photo-cell was switched on as was also the "Beam Switch" of the oscilloscope. The small motor driving the four-segment disc used in the emissivity test was started. As the entire film was run through the camera in approximately 1-1/2 seconds, it was imperative that the switching on of the camera be effected by one operator who carefully observed the deflection on the oscilloscope screen while another operator assumed responsibility for both starting the engine and injecting the additive. At the start of the test, therefore, the latter operator switched on the starting spark and aspirated fuel into the combustion chamber using an auxiliary compressed-air supply. Difficulty experienced in starting the jet engine was usually overcome by pre-heating the entire unit with the aid of an ordinary infra-red heating lamp. Once stable operation of the jet had been attained over a five-second period of time, the jet operator threw on the blower-injector switch forcing a stream of salt dust into the valve-bank of the engine. Meanwhile, the "camera" operator observed the oscilloscope screen and, when the single spot on the screen expanded into a line trace some three inches long consequent upon the start of additive injection, made the mains switch to the camera. The entire procedure from the initial starting of the engine to the final switching off of the camera motors occupied approximately fifteen seconds: this period was sufficient for the jet to attain a brilliant red heat. The entire valve-bank of the jet was then removed and thoroughly cleaned in preparation for the next test.

Following a test-run on the engine, the spectrophotometer was calibrated as follows. The engine, the emissivity test apparatus and the blast screen were removed and the furnace placed approximately in position. The mains switch to the furnace was made and heating of the black-body cavity commenced at the rate of a five-ampere increase of the transformer primary current per each ten minute interval until the cavity reached a bright red heat. At this point, the heating current was maintained constant while the position of the furnace was accurately adjusted until the auxiliary bi-convex lens produced an image of unity magnification of the aperture of the cavity on the entrance slit of the spectrophotometer. This adjustment was facilitated by the provision of a thin aluminium sheet placed over the slit into which a circular hole equal in area to the aperture had been cut with its centre at the middle of the slit. The bright image of the aperture fell on the aluminium sheet and the position of the furnace was adjusted until the image just filled the hole in front of the slit. Having completed this preliminary adjustment, the furnace was raised through a series of temperatures from 800 to 1500 degrees Centigrade (these temperatures being measured by means of the disappearing filament pyrometer as formerly described) and the deflection of the oscilloscope beam corresponding to each particular temperature marked on the screen using a fine pen and India ink. Following this procedure, the furnace was allowed to cool slowly while the several deflections of the beam as marked on the oscilloscope screen were measured using an accurate pair of dividers and a steel rule. Typical calibration data is given in Table 2 below.

TABLE 2

Cavity Temperature			Oscilloscope Deflection
Degrees F	Degrees C	Degrees K	Inches
2300	1262	1535	2.3_8
2262	1240	1513	1.9_6
2242	1230	1503	1.6_6
2230	1223	1496	1.6_3
2220	1219	1492	1.4_9
2110	1157	1430	0.8_0
2020	1105	1378	0.5_4

TABLE 2 (Cont'd)

Cavity Temperature			Oscilloscope Deflection
Degrees F	Degrees C	Degrees K	Inches
1965	1072	1345	0.4_7
1880	1028	1301	0.2_6
1790	976	1249	0.1_3
1760	959	1232	0.0_7

Note: The practical limit of "Cut-off" of the thermally excited "D" line radiation was estimated to occur at 950 degrees Centigrade.

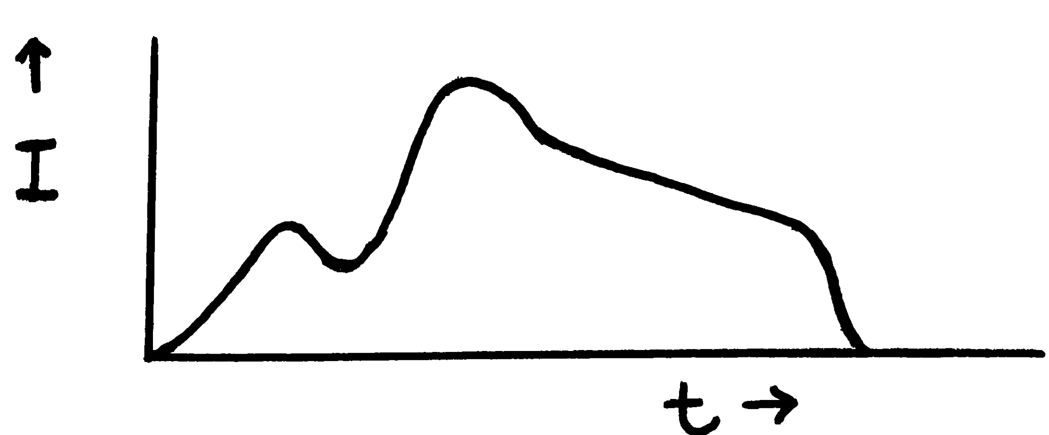
Using the data as contained in the above Table and assuming sufficient linearity of both the photo-cell D-C amplifier and the oscilloscope tube, a graph was plotted of Logarithm to the base "e" of the intensity as measured by the beam deflection against the reciprocal of the Absolute temperature corresponding to the particular beam deflection. This graph is illustrated in Fig. 12 where it will be immediately noted that the several points corresponding to small beam deflections show a considerable scattering: this is to be expected due to the difficulty of measurement of the smaller beam deflections. It was anticipated that the radiation intensity from the cavity would follow the Planck Law to a close approximation. The modified form of this Law due to Wien being considered adequate over the temperature range encountered here, the form of the above graph should be a straight line: Fig. 12 shows that this linear relation was obtained to a close approximation, apart from the points corresponding to small beam deflections as noted above. The measured slope of the line of Fig. 12 differs from the theoretically calculated value by only 1.2%: this agreement was taken to indicate the achievement of satisfactory black-body conditions in the cavity. The final calibration curve for the spectrophotometer-oscilloscope combination was then derived from the above graph and appears in Fig. 14. It will be noted that the thermally excited "D" line radiation tended to a practical "cut-off" at 950 degrees Centigrade.

The conversion from the Intensity-Time record on the film to the final Temperature-Time relationship was effected as follows. Two marks were provided on the screen of the cathode ray tube of the oscilloscope; the distance between these marks was accurately measured using the dividers and steel rule and, finally, the marks were photographed by the camera. The negative so obtained was placed in a Kodak Precision Enlarger and the latter adjusted until the distance between the images of the above marks projected on a plane white surface equalled the distance originally measured on the screen. Having made this adjustment of the enlarger, it was simply necessary to project any particular intensity-time cycle on the white surface and to use the calibration curve of Fig. 14 to obtain the temperature-time relationship.

ANALYSIS OF THE DATA AND RESULTS

The results which follow have been derived from a study of some six hundred feet of film constituting the intensity-time records for twelve separate test-runs of the jet engine. It is immediately apparent, on examination of each individual record, that a general dissimilarity exists in the intensity-time wave-forms obtained from cycle to cycle of the engine. This situation is clearly illustrated in Fig. 15-A where the wave-forms corresponding to several cycles recorded before the camera reached its maximum operating speed of 25 feet per second are shown. When the number of uncontrollable factors which influence the operation of this particular type of engine are considered (particularly the nature of the fuel injection system which cannot possibly be expected to provide a constant air/fuel ratio) it is indeed remarkable that any consistency among the above wave-forms should be obtained at all. A definite consistency between some individual wave-forms has, however, been definitely established in this research.

In the examination of the several records, it was considered adviseable to look for two particular points of similarity in the intensity-time wave-forms: (1) equality of the maximum intensity (corresponding to the maximum temperature attained) recorded during the cycle and (2) similarity of the general configuration of the separate wave-forms. Analysis of the films according to this procedure indicates that one particular type of wave-form occurs repeatedly at irregular intervals throughout each film record: the configuration of this most recurrent wave-form is illustrated in the rough sketch which appears below:



In one particular record, a complete set of four wave-forms of this type appears: this set is shown in Fig. 15-B.

As previously stated, the original form of test designed to establish the existence of the requisite black-body conditions in the exhaust flame did not give positive results in that no alternate sets of four large and four small intensity-time wave-forms were ever obtained, the maximum intensity and general configuration varying widely from cycle to cycle. It has, however, been possible to show the existence of similar cycles scattered at random throughout the records and, by means of the micro-switch-Strobotac arrangement, to indicate for each particular cycle whether the reflecting mirror was either exposed or screened. Figs. 16 to 21 illustrate selected similar cycles and in each case it has been noted on the figure whether or not the mirror was exposed: this procedure has given fairly conclusive evidence that the required conditions were obtained over limited intervals in the test-runs.

The existence of the above recurrent, similar cycles admits of two separate interpretations: (1) there is a unique temperature-time variation in the exhaust gases and, in the cases of the above cycles, black-body conditions were established in the exhaust flame or, (2) the temperature-time relationship in the exhaust flame varies from cycle to cycle, black-body conditions were not established in the flame and the above similarity results only from a fortuitous combination of several factors. These factors are (a) the particular temperature-time variation for a particular cycle, (b) the particular concentrations of the additive present in the exhaust flame at all times during the cycle and, (c) the effect of additional light received by the spectrophotometer in those cases where the mirror was exposed. Clearly the former interpretation is the most logical one and this interpretation has been given here.

An interpretation of the consistent cycles has been given; this does not, however, help to explain the wide dissimilarity generally observed from cycle to cycle. Studies of the behaviour of the engine at the beginning of additive injection revealed immediate and definite changes in its operating characteristics: both the "note" of the engine and the length of the exhaust flame changed abruptly. These effects were most prominent in one particular engine test where a particularly finely powdered salt dust was used and they suggest that considerable perturbation of the combustion process in the engine is effected by the addition of the large quantity of additive required to produce black-body conditions in the exhaust flame. This disturbance of the normal combustion process in the engine would clearly explain the wide variations obtained from cycle to cycle in the exhaust temperature-time wave-forms. It is considered, however, that at some particular intervals during the recording period, the concentration of the additive in the engine was adequate to effect the requisite conditions in the exhaust flame without seriously perturbing the main combustion process and that the consistent cycles formerly described were recorded during such intervals.

Referring to Fig. 15-B, it will be noted that the intensity-time wave-form returns to a "zero intensity" level over a large portion of the complete cycle of the engine: this complete cycle of the engine is here defined as the time interval between the instant when the wave-form begins to rise from the "zero" line to the corresponding point on the succeeding wave-form. Examination of the film records has revealed two further important results: (1) the period of a complete engine cycle is a constant -4.97 milliseconds and, (2) the time interval occupied by the wave-form in rising from the zero line and returning thereto is also a constant -2.39 milliseconds. Result (1) gives an operating frequency of 201 cycles per second for the pulse-jet used in this particular research.

The return of the wave-form to the zero level over a large portion of the operating cycle is due to two separate factors. The present apparatus is unable to detect thermally excited "D" line radiation emitted by a source whose temperature is less than 950 degrees Centigrade as illustrated in Fig. 14. In the absence of evidence from other investigations revealing a more surprising reason, it might be reasonably assumed that, at the periods of zero intensity, the exhaust gases simply fell to temperatures below the above limit. It has, however, been definitely established by Hudson and Hett[24] in their investigations of the pulse-jet exhaust flame by means of high-speed photographic techniques that, following the initial outflow of the exhaust flame shortly after the beginning of a particular engine cycle, a period of flow reversal occurs wherein the exhaust flame appears to contract in diameter and then to vanish backwards into the tail-pipe of the engine. It is here considered that both of the above effects operated to give the wave-forms observed in this research; the exhaust gases probably fell first to much lower temperatures than 950 degrees and then were effectively swept out of the field of view of the spectrophotometer being replaced by atmospheric air at room temperature.

Considering now the range of temperatures which can be measured with the present apparatus, the practical lower limit of this range has already been seen to be 950 degrees Centigrade. There is, however, no theoretical upper limit to the measurable temperature range insofar as the maximum temperature which can be recorded using this type of technique is controlled only by the saturation current of the particular photo-electric cell employed as the radiation detector, the ability of the D-C amplifier to handle a large input voltage signal and, finally, the size of the cathode ray tube required to present the deflection corresponding to the maximum temperature. The particular photo-cell, D-C amplifier and oscilloscope tube combination as used in the present research enables an upper-limit temperature of 1350 degrees Centigrade to be measured.

The appearance of the "secondary maximum" of intensity near the beginning of the intensity-time wave-form was, at first, regarded as being extremely peculiar insofar as it was difficult to explain a sudden drop in the temperature of the exhaust gases shortly after the outflow of the latter commenced. This peculiar drop in temperature has, however, been strikingly co-related with some early high-speed photographic results due to Hudson and Hett[26]. These investigators showed that flame propagation in the pulse-jet takes place in the following manner: upon ignition of the air/fuel mixture in the combustion chamber, a small knot of flame (termed a "flambeau" by Hett) is rapidly propagated throughout the length of the engine, finally emerging at the end of the tail-pipe; this preliminary "flambeau" is followed, after a brief period of no visible burning, by a marked band of flame travelling some four inches behind the flambeau. The occurrence of the above secondary maximum is, therefore, interpreted here to correspond to arrival at the extremity of the tail-pipe of the high temperature section of the flambeau while the succeeding upward rise to the main maximum is taken to correspond to the arrival of the main flame.

When considering the selected cycles as illustrated in Figs. 16 to 21, the logarithmic relation between the recorded intensity and the actual temperature must be continually borne in mind: in particular it must be realized that, at the higher temperatures, a small change in temperature results in a very disproportionate change in intensity. To make this point clear, the temperature-time graphs obtained from the particular cycles of Fig. 16 and Fig. ~~17~~ 20 are shown in Fig. 23. Both curves indicate a secondary maximum of temperature occurring some 1.0 milli-seconds after the beginning of initial upward temperature gradient; moreover, the general configuration of the curves and their maximum temperatures are strikingly similar. Fig. 24 shows the temperature-time curves for the particular cycles of Fig. 17 and Fig. 18.

As minor differences are still apparent between the above curves, it has been decided to select the curve 1 of Fig. 23 as representing an average relationship and this particular curve has, therefore, been taken to constitute the considered temperature-time variation for the exhaust flame.

On the basis of information received during the last few months from those research laboratories in the United States where investigations of the pulse-jet are at present in progress, it can be stated that the above results constitute the first published figures for the temperature variations at the engine exhaust. It is, however, very possible that other similar data has been published by other workers in some of the confidential reports of government agencies or sub-contractors.

DESCRIPTION OF AN ALTERNATE SPECTROPHOTOMETRIC TECHNIQUE

In the investigation of the temperature-time relationship for the exhaust flame of the pulse-jet just described, an attempt has been made to effect monochromatic black-body conditions for the narrow spectral region occupied by the sodium "D" lines. The difficulty experienced in obtaining adequate injection of the additive to effect the above condition, the difficulty of devising a positive test for the black-body conditions, not to mention the serious perturbation of the combustion process in the engine by the amount of additive supplied, have all been examined in detail. The original method is clearly not appropriate for routine engine testing.

Accordingly, an alternate radiation method employing only a minute quantity of additive (substances) has been sought. The technique which is now suggested depends upon the injection of only a small quantity of additive sufficient to give rise to "Boltzmann" radiation from the hot gases, in lieu of the much larger amount required to give the "Planck" radiation as formerly utilized.

Let there be added to the engine fuel small quantities of organic salts of both sodium and lithium. These salts should be completely soluble in gasoline and their concentrations adjusted experimentally in order to obtain sufficient radiation at the wave-lengths of both the sodium "D" line at 5890 Å and the lithium red resonance line to affect a sensitive photo-cell of the 931-A type. The relative radiation intensities of the above yellow and red lines can theoretically be obtained from the Boltzmann Radiation Formula:

$$\mathcal{J}_Y = A_j N_j h\nu_Y = A_j h \nu_Y N_S e^{\frac{-E_j}{KT}} \frac{g_j}{Z_S}$$

and,

$$\mathcal{J}_r = A_i N_i h\nu_r = A_i h \nu_r N_L e^{\frac{-E_i}{KT}} \frac{g_i}{Z_L}$$

by some non-selective type of radiometer) either at the yellow or the red wave-lengths produce equal deflections of the beam of a cathode ray oscilloscope. All that remains, therefore, is to present the amplified output of each cell on a separate oscilloscope screen and to photograph the separate deflections simultaneously with a high-speed camera. The resulting film can thereafter be enlarged and the ratio of the separate intensities measured directly on the enlargement. It is conceivable that some form of electronic circuit might be devised whereby the ratio of the outputs of the cells (corrected for their individual response curves) might be obtained directly and a deflection proportional to this ratio provided on the screen of a single oscilloscope. This would reduce the labour involved in the computation of the final temperature-time curve.

It is to be noted that this proposed alternate method will have one major disadvantage in common with the former technique; the lowest temperature which it can be expected to measure will be of the order of 900 degrees Centigrade. To obtain the temperature-time relationship below 950 degrees Centigrade, it is apparent that some form of radiation method utilizing radiation in the infra-red region of the spectrum will have to be devised.

BIBLIOGRAPHY

(0) S.A.E. Quarterly, April 1947.

(1) MacDonald, A Gas Dynamical Formulation for Waves and Combustion in Pulse-Jets, Report of the Applied Mathematics Group, New York University, 1946.

(2) Graff, VDI-Zeitschrift, Vol. 86, No. 29-30, July 25th, 1942.

(3) Waggener, Verhandl. der Physik. Ges. 14, 78, 1895.

(4) Burkenbusch, Wied. Ann. 67, 649, 1895.

(5) Nicols, Phys. Rev. 10, 234, 1900.

(6) Kurlbaum, Phys. Zeits. 3, 187, 332, 1902.

(7) Fery, Comptes Rendus, 137, 1903.

(8) Kurlbaum and Schulze, Deut. Phys. Ges. 5, 428, 1903.

(9) Griffiths and Awbery, Proc. Roy. Soc. Series A, 123, 1929.

(10) Loomis and Perrot, J. Ind. and Eng. Chem., 1004, 1928.

(11) Loomis and Perrot., Am. Phys. Soc. Trans. Vol. 26, 1928.

(12) Ruark and Urey, Atoms, Molecules and Quanta (Text).

(13) Hershey and Patton, Eng. Expt. Sta. U. Illinois Bulletin No. 262, 1933.

(14) Watts and Lloyd Evans, Proc. Phys. Soc. (London) 46, 1934.

(15) Rassweiler and Withrow, J.S.A.E. 36, 4, 1935.

(16) Brevoort, Rev. Sci. Inst. 7, 342, 1936.

(17) Ribaud, Laure and Gaudry, Jour. Inst. of Fuel, 12, (64), S-18, 1939.

(18) Schmidt, Deut. Phys. Ges. Pg. 90, 1909.

(19) Lewis and Von Elbe, Combustion, Flames and Explosions of Gases (Text).

(20) Bauer, 'Recherches sur le rayonnement', These, Paris, 1912.

(21) Smit, Physica, Vol. 12, 1946.

(22) MacDonald and Quinn, United States Navy Project "Squid", Semi-Annual Progress Report, Jan. 1947.

(23) Artz, Electronics, Aug. 1945.

(24) Hett, United States Navy Project "Squid", Semi-Annual Progress

(25) Mellor, Inorganic and Theoretical Chemistry, Vol. II (Text).

(26) Hett, United States Navy Project "Squid", Semi-Annual Progress Report, Jan. 1, 1947.