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PROPAGATION OF ELECTROMAGNETIC WAVES THROUGH PROPELLANT GASES

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Approved by:

Dr. R. M. Page, Superintendent, Radio Division III

Problem No. 36R25-03 November 6, 1947

NAVAL RESEARCH LABORATORY

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FOREWORD

Much of the material in this report formed the Naval Research Laboratory contribution to a conference called by the Office of Naval Research in the interest of summarizing current flame research studies.

ABSTRACT

This interim report contains a qualitative analysis of the subject problem (NRL Problem 36R25-03 "Propagation of Electromagnetic Waves through Propellent Gases") including some comments on nomenclature and instrumentation difficulties. It also sets forth the reported and unreported activities of the Naval Research Laboratory in various fields of approach to the problem by indicating what data have been collected and the status of its analysis. In addition, some salient aspects of future endeavor toward a conclusion of the study are indicated.

PROBLEM STATUS

This is an interim report on this problem; work is continuing.

PROPAGATION OF ELECTROMAGNETIC WAVES THROUGH PROPELLANT GASES

INTRODUCTION

Many investigators have found that the propagation of radiant energy through propellant gases of reaction motors is accompanied by absorption of energy. The absorption is reported in varying degree depending upon fuels, motor rating, and instrumentation. In addition, some studies indicate that propagation is attended by incidental modulation of the radiant energy impinging upon the flame and flame trail. Thousands of man hours have been devoted to basic research in this field, both in this country and abroad, with evidence to date indicating that further investigations are needed before a complete understanding is realized or suitable correlation attained. Some things are known with reasonable surety, but further research is required before suitable data can be made available to design with certainty a missile, power plant, and radio control combination; or to eliminate or minimize unwanted physical propagation characteristics, if indeed such is possible.

Flames and flame trails impose upon electromagnetic propagation free charge and molecular conditions resulting from a chain of events when fuel components plus their contamination react chemically and thermodynamically to produce, for the most part, a volume of mixed gases at relatively high temperature and pressure. By proper combustion-chamber and venturi design, the gas is handled so as to expand adiabatically as a continuous-stroke motor * to produce a mechanical thrust. Since altitude changes the motor back pressure, flame dimensions and some after-burning conditions are thereby materially changed.

The Naval Research Laboratory has actively pursued the general problem of electromagnetic propagation through propellant gases, as well as closely allied work, for a period of approximately two and one-half years, starting early in 1945. Certain personnel of the Rocket Sonde Section of the former Electronics Special Research Division (now Radio Division I) pioneered at this laboratory in both liquid and solid fuel flame investigations, including the V-1 resojet and the Westinghouse turbo-jet. This group is presently, and has been for some period, active with measurements of the V-2 missile flame.

On or about 1 December 1946, Naval Research Laboratory activity in this special field was increased when one section of Radio Division III assumed responsibility for the problem A-140R-C, with their immediate interest that portion of the problem especially pertinent to the Lark missile program. The activity of this group has now reached a point where experimental and theoretical attack of more general application is in progress or proposed for future work.

* With either continuous- or pulsing-stroke motors, when the fuel oxidizer is obtained from the medium the term "jet" is applicable. If the oxidizer is carried as a fuel component, the term "flame" is preferable. The term "flame" will be used henceforth in this report to indicate either a flame or jet; exhaust components not visible to the eye will be referred to as the "flame trail".

Mention is made of the recently active part taken by some personnel of the Optics Division of the Naval Research Laboratory. This group, cooperating with Radio Division III field trips, has accomplished exploratory temperature measurements of the acid-aniline flames of the Lark motors and the oxygen-alcohol flames of the basic single motor which comprises, in quadruple mount, one power plant of the XS-1 aircraft. The Chemistry Division of the Naval Research Laboratory has been helpful and cooperative by undertaking fuel sample analyses of raw aniline and other substances for both Radio Division I and III, the aniline analysis being particularly helpful to Radio Division III in the study of certain total magnetic field properties of acid-aniline and other flames.

There is additional basic research activity carried out by other Divisions and Sections of the Naval Research Laboratory which, at some future date, may reveal findings which it is believed will be applicable to a more thorough understanding of the flame problem. The foregoing indicates the spread of general activity on the subject problem which is formally centered in two Radio Divisions with other Divisions and Sections of the laboratory cooperating informally.

PROBLEM ANALYSIS

The general problem is herein broken down into some main component parts for future consideration of certain aspects. This treatment will allow this report, in one respect, to be a preamble (by reference) to a number of subsequent reports by Radio Division III on different aspects of the general subject. Although this may not be the most elegant method of disseminating information, it is believed to be one which will provide quick circulation of findings without one aspect of the problem being impeded by the time schedule of another. This report is also written to indicate the scope of and activity on the subject problem at the Naval Research Laboratory. Thus, the report sets forth, on a laboratory basis, what has been accomplished, what work is in progress, and the nature of some approaching plans.

Suffice it to say that there are a number of physical factors which determine the quasi-optical properties of propellant gases. Of immediate interest in any air program requiring the use of reaction motors is the nature and extent to which radiant energy is redistributed or absorbed when directed upon the flame or flame trail. If such physical factors be of prime importance, the complex incidental modulation of the incident energy is no less important, because the success of a missile control system, for example, will depend upon both the nature and degree of this incidental modulation.

Disregarding some of the limitations we live with from day to day, it can be stated that no particular difficulty is experienced in propagating electromagnetic waves through a non-ionized medium. The contamination of this medium, however, by free charge and molecular conditions allows for energy reradiation as well as irretrievable energy extraction from the field due to the absence of restoration forces or the existence of energy sinks where quantum conditions of any order exist. In effect, for this problem we deplore the presence of physical conditions for which in some other instance we would see invaluable use.

The nature and extent of any adverse propagation and incidental modulation conditions and the degree of success one might have in alleviating any difficulties, are functions of many interrelated physical factors including the following:

(a) The frequency of the incident wave.

(b) Incident angle (not angle of incidence) of the energy density vector in question.
(c) Free-charge volume density distribution in both flame and trail.
(d) Physical size of the flame in relation to the free space wavelength of the incident radiation.
(e) Percent of radiant energy which falls in a region that may be affected by the flame and trail.
(f) Types of fuel and combustion components.
(g) Fuel and oxidizer contamination (low ionization potential impurities, particularly alkali and rare earth traces).
(h) Uniformity or non-uniformity of combustion (raw fuel is often expelled accidentally or by design for after-burning; also excess servo fluid may be expanded overboard via the flame).
(i) Volume distribution of flame temperature (random cooling and reignition can take place and one must be certain as to what is meant by flame temperature).
(j) Reaction motor back pressure (change of flame conditions and dimensions with altitude and mach number).
(k) Internal flame pressure and pressure distribution.
(l) Quantum absorption conditions and pressure broadening effects.
(m) Superimposed magnetic field (along with temperature and flame pressure this contributes to collision frequency).
(n) Flame and radiator proximity (whether or not the flame is in the near zone of the antenna).

The propagation problem is one for electromagnetic and quantum theory, though it is obviously one which does not lead itself to easy application in the first instance. To apply theory rigorously, flame boundary conditions and physical states are required which are not all known. Disregarding the simplifications already practiced, it is the lack of knowledge of such things as volume distribution of temperature, electron collision frequency data, and an impressive amount of other information which relegate formal attack on the main problem to second place until experimental data obtained on the individual building blocks are in hand. One would not be surprised if the experimental attack on the main problem is the one which brings fruitful results more quickly, because the complex geometry of flame non-uniformity may prohibit formal treatment of such a radiation barrier.

Attenuation–one aspect of the whole quasi-optical problem–has received considerable attention, and not without judicious reasoning when one considers the physical states involved. The presence of free electrons dictates a medium with a real dielectric constant less than unity; dissipation of energy by molecular absorption or transfer of energy to the main gas mass by inelastic collisions calls for less disparity from unity and a dielectric constant of complex form. A dielectric constant less than unity is indicative of a phase velocity greater than the velocity constant of light. The energy, however, can never travel faster than the latter constant, when one recalls the concept employed by Stokes and Rayleigh in relating phase and group velocity. The theoretical aspects of attenuation due to the presence of free electrons or molecular conditions is established by prior art and need not be mathematically detailed here. Any energy absorbed from the field in such a manner as to be characterized as irretrievable in form is caused by the absence of mechanical restoration forces and/or molecular states acting as energy sinks. The energy absorbed by "sympathetic" electrons can be reradiated. It can also be withdrawn from the field in unavailable form to appear as an increase in random molecular energy. The degree to which the latter takes place determines the redistribution of energy and contributes to the numerical value of the electron collision frequency.

Due to inadequate knowledge of the flame,* the theory of incidental modulation of incident radiant energy is not in a quantitative form, though physical reasoning indicates that such modulation can be of complex form. A fluctuation of the dielectric constant of the in-flame medium due to temperature and pressure conditions as a function of space and time could cause random modulation, sustained tone modulation, or a mixture of both. It could also be caused by flame whipping when the incident angle of the radiant vector is large, whether or not the conditions for appreciable attenuation exist.

PROBLEM STATUS

In the present state of the art, and apart from the experimental attack by actual field measurements, some isolated theoretical aspects of the whole problem have been and are receiving formal treatment. The situation, however, is a long way from determining the quasi-optical performance at operating frequency f_1 of a 1500-lb-thrust oxygen-alcohol flame from data obtained on a 400-lb-thrust acid-aniline flame subjected to radiant energy of frequency f_2. This statement is true even between flames of the same type but of different thrust rating.

With regard to incidental modulation, much of the existing information indicates an uncertainity on the part of a number of observers as to whether what they observed was genuine incidental modulation or microphonic difficulties with equipment. This statement is particularly true where sustained tone modulation evidenced itself. It is appropriate at this juncture to state that field measurements associated with this problem can readily produce honest data of a questionable nature.

It is also timely to set forth that flames must be non-uniform in nature to produce a mechanical thrust. Some current uses and treatments of flame attenuation data ignore flame non-uniformity and still require the correct answer to the question, "what are the temperature and electromagnetic dimensions of a flame?" Any answers to this question are complicated because of the material changes in the character and dimensions of a flame and trail between the limits set by motors operating in static thrust and those in dynamic flight through some altitude function with time.

There is excellent evidence from a number of sources that the presence of low ionization potential salts materially augments attenuation and that attenuation figures on solid fuel performance are higher than those obtained with liquid fuels. In addition, liquid fuel flames with solid fuel ignitors indicate higher attenuation during the period that the ignition is active.

There is considerable variation in attenuation data presented on a db-per-meter basis when comparisons are made among different observers. Some of the inequality is due to uncertainty of flame dimensions, fuel contamination, and methods of instrumentation; the remainder due, perhaps, to an over-simplification of the problem by assuming flame uniformity. In support of some of the foregoing remarks on attenuation and flame dimensions, it is also noted that transverse-flame propagation data on a db-per-meter basis do not agree with nearly longitudinal-flame propagation figures on the same motor flame. There is some misgiving that db-per-unit-length data is not always accompanied by region-of-entry data on the flame, electromagnetic flame dimensions, and temperature measurements. There is purpose in evolving a comparison unit of measurement if the results of widely separated investigators, operating with different experimental conditions,

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* Much prior art deals with soft flames. A hard flame, for want of better words, may be considered as one containing Mach nodes.

can be placed on a common basis. However, it may be unwarranted to employ db-per-meter data in many cases. This statement can be disturbing, yet a review of the physical factors leave little choice in the matter. Apart from flame non-uniformity, a redistribution of radiant energy vectors incident upon a flame can take place, and when not accounted for, the db-per-meter information or any charge density data drawn therefrom, will have less quantitative meaning. Thus, transverse-flame and down-flame uniformity in performance should not be expected, and the db-per-unit-length data examined with extreme care.

With regard to flame dimensions it is recalled that the camera, with different exposures and film emulsions, "sees" quite different flame and trail dimensions. With regard to temperature there is one condition of a visibily opaque flame trying to act as a black body radiator. Its temperature may be described at any point by the temperature of carbon particles entrained. Then there is the visibly transparent flame which leaves the "foot-prints" of a line spectrum where temperature has a physical significance also. The use of temperature as applied to flames whether soft (low velocity) or hard (high velocity) requires more than loosely extracting a value for one point only.

NAVAL RESEARCH LABORATORY ACTIVITY

That which has been accomplished at the Naval Research Laboratory on the problem at hand divides itself into both laboratory and field investigation activity. Considerable data have accumulated by previous pioneering work and past measurements on the V-2 missile. Much has also accumulated from quasi-optical studies and other physical measurements made on the flames of acid-aniline and oxygen-alcohol motors operating in static thrust. The V-2 studies are a primary activity of Radio Division I; the latter that of Radio Division III, being the work of two field trips to Reaction Motors, Incorporated, Dover, New Jersey, during 12-20 March 1947 and 23-30 June 1947.

There follows a condensed statement on each particular phase of work related to the subject problem. Some portions of the problem have been reduced to formal reports or certain aspects have been reported upon in a preliminary form via conferences where findings could be applied to other immediate problems at hand. Where formal reports or formal conference reports exist such will be noted. However, in numerous instances the content will indicate that information will be available when accumulated data have been completely analyzed. Activity on the numerous phases of the problem are set forth on a Division basis as an assistance to the reader who seeks certain information and the source from which it has evolved or may evolve.

RADIO DIVISION I ACTIVITY

Early in 1945, X-band and S-band transverse-flame attenuation measurements were made on a 300-lb-thrust acid-aniline motor by employing a single emitter and receptor. A 6-db-per-meter attenuation was measured, but it is well to point out that the flame was small in diameter and the measured value across the flame was much smaller than this figure. The results of this investigation are presented in an NRL letter report. *

* NRL Letter Report S-F42-1/84 (320:LMH-CHH) Ser. 5195, 28 July 1945, now classified Confidential.

L- and X-band transverse-flame measurements have been made on the German V-2 rocket. The X-band data are treated in NRL Reports R-2956* and R-3031†; other data are in the process of analysis.

Spectrogram measurements (visible region) have been made on the German V-2 rocket flame to determine the salt content. These data are in the process of analysis.

Theoretical attenuation studies, with corresponding laboratory investigations on an oxygen-alcohol flame operating under controlled conditions, have been made with particular attention to the effects of the introduction of known quantities of selected salts. It is felt that the measured values of attenuation obtained under these conditions agree quite well with theoretical predictions. The results of this work are presented in the letter report mentioned on page 5.

Quantitative values of electron collision frequency and electron volume density have been determined, in the absence of incident radiant energy, by the flame probe method employing a d-c source. Early measurements indicated electron densities which agreed with computed values, except at quite low values of electron densities (10^8 /cc). More recent experiments, however, have indicated that computations of r-f attenuation on this basis is open to serious question.

Photographic studies of V-2 flame taken in flight show flame expansion and boundary changes.

OPTICS DIVISION ACTIVITY

Exploratory flame temperature measurements employing quartz prism spectrographic and total radiation pyrometers have been made on the acid-aniline motors of the Lark missile. These measurements were made as part of the aims of the field party which studied the Lark missile motors in static thrust at Reaction Motors, Incorporated, Lake Denmark (Dover), N. J., 12-20 March 1947. A detailed report of this particular study is found in NRL Report No. N-3097‡, which includes analysis of the acid-aniline flame spectrum.

During the field trip to Reaction Motors, Incorporated, 23-30 June 1947, further temperature measurements were made on the Lark missile motors and a 1500-lb-thrust oxygen-alcohol motor. These data are now in the process of analysis.

RADIO DIVISION III ACTIVITY

The activities of this division stem from a variety of data accumulated from participation in two comparatively recent field trips. These trips involved equipping a mobile laboratory suitable for the desired measurements planned for each occasion, and in the main constituted quasi-optical studies of both acid-aniline (Lark) and oxygen (XS-1) motors operating in static thrust. Such measurements were made possible by the

* Becker, Bourdeau, Burnight, Fry, "Upper Atmosphere Research, Report I, Part II," NRL Report No. R-2956, Confidential, October 1946.

† Becker, Bourdeau, Burnight, "Upper Atmosphere Research. Report II, Part II," NRL Report No. R-3031, Confidential, December 1946.

‡ Curcio, J. A., and Butler, C. P., "Optical Radiation from Acid-Aniline Jet Flames," NRL Report No. N-3097, Confidential, July 1947.

combined facilities of the Naval Ammunition Depot and Reaction Motors, Incorporated, both of Lake Denmark (Dover), New Jersey.

S-band quasi-optical propagation data has been taken on the Lark missile motors with polarization, frequency, and simulated missile motor operation as variables. The propagation data consists of near-longitudinal and transverse-flame measurements, including exploration for any umbra or penumbra type shadow formations attributable to abnormal dielectric constant or after burning conditions. A preliminary survey of this study is included in NRL Report No. R-3070 * and a preliminary report of the results of this investigation, made 12-20 March 1947, may be found in NRL Report R-3108†. A further investigation was carried out 23-30 June 1947 and a complete data analysis is still in progress with formal reports in plan.

Exploratory X-band propagation measurements, both transverse and near-longitudinal flame, have been made on the 400-lb-thrust motor of the Lark motor compliment. The propagation data obtained is considered important, particularly as it may assist in the evaluation of a philosophy of instrumentation. These data taken 23-30 June 1947, are now in the process of analysis.

Exploratory X- and K-band propagation data, both transverse and down-flame, have been taken on a 1500-lb-thrust oxygen-alcohol unit, being a single unit of a quadruple mount which forms but one power plant of the XS-1 aircraft. This work was performed to evaluate an instrumentation philosophy as well as obtain the propagation data. These data, taken 23-30 June 1947, are now in the process of analysis.

Photographic data of the Lark missile flames and a 1500-lb-thrust oxygen-alcohol flame were taken by employing exposure step-wedges and a selected group of emulsions. This work was performed in an attempt to quantify flame non-uniformity by possibly revealing a relative temperature distribution which would be useful for charge-density studies. These data, taken 23-30 June 1947, are in the process of analysis.

Data were taken on the 400-lb-thrust Lark motor at S-band frequencies for voltage standing wave ratio measurements of a dish-reflector (dipole type) antenna as a function of spacing from the flame. The flame and antenna combination constituted a near-zone condition for the antenna and indicated that any noticeable effects were absent, quite unlike metal and dielectric barriers. These measurements, in conjunction with transverse-flame studies, indicated effective flame transparency at the incident energy frequency.

Incidental modulation of S-band radiant energy was studied on the Lark missile motors under both transverse and near-down-flame conditions. These data were taken in conjunction with flame light intensity (visible), motor mount vibration, and accoustical field intensity, all as functions of time.

The data accumulated in this aspect of the problem was taken during 12-20 March (preliminary report in NRL Report No. R-3108) and 23-30 June 1947. A detailed report covering the work of both periods is in process.

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* Locke, A. S., "Lark-Wasp Guided Missile Seminar," NRL Report No. R-3070, Confidential, January 1947.

† Locke, A. S., "Lark-Wasp Guided Missile Seminar," NRL Report No. R-3108, Confidential, April 1947.

Exploratory magnetic-field measurements in the vicinity of the flames of both the 400-lb-thrust acid-aniline motor of the Lark missile and a 1500-lb-thrust oxygen-alcohol motor have been made on the basis that the motors expel charge. In a quantitative manner it can be stated that there is a considerable change in total magnetic field in the vicinity of these flames. These data were taken during the periods 12-20 March and 23-30 June 1947. Other measurements are in the planning stage, with a report on the findings in process. Some preliminary mention of this work is found in NRL Report R-3108.

S-band noise-level data has been taken, considering the Lark motors' flames as possible sources, with the aid of special composite receiving equipment. The data was taken during the period 23-30 June 1947 and is in the process of analysis.

Exploratory electrostatic lens and charge deflection data have been obtained on a 400-lb-thrust acid-aniline motor as well as on a laboratory-type, separately oxidized fuel flame; current-voltage studies have also been made. These data were taken during the period 12-20 March 1947 and thereafter. A portion of one full time project is now devoted to a further study in this field.

FUTURE PLANS

Apart from the foregoing, which indicates that a number of formal reports are in process and other types of investigative work are planned or still in progress, some of the salient features of the relatively near future activity on the subject problem include:

1. Attenuation measurements on the V-2 missile flame at frequencies other than X- and L-band. In addition, spectroscopic studies relating to flame temperature are planned.
2. Specific studies involving a limited production model of the Lark missile receiver are planned to determine motor vibration effects, inherent flame noise levels, and the change in signal level required to maintain "control" in the presence of a simulated missile motor firing in static thrust.
3. Consideration is to be given the flame study instrumentation problem from the standpoint of obtaining quasi-optical phenomena over a band of frequencies in more than one observation plane external to the flame and within the flame. It is desirable to obtain large quantities of data in a short time with a minimum of man-power.
4. More detailed plans of Radio Division I are indicated in NRL Report No. R-3139*.

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* Newell, H. E., and Siry, J. W., "Upper Atmosphere Research, Report III, Part II," NRL Report No. R-3139, Confidential, April 1947.

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