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FINAL REPORT

Contract No. NASW-1775

INVESTIGATION OF FLAME FRONT PHENOMENA - EFFECTS OF IMPRESSED ACOUSTICAL FIELDS

Prepared by

Robert L. Durfee
Jack M. Spurlock

Submitted to

Chief, Fluid Dynamics Branch
Code RRF
National Aeronautics and Space Administration
Washington, D.C.

Submitted by

Atlantic Research Corporation
A Division of The Susquehanna Corporation
Shirley Highway at Edsall Road
Alexandria, Virginia
22314

ARC No. 43-5440

June 6, 1969

ATLANTIC RESEARCH

A DIVISION OF THE SUSQUEHANNA CORPORATION

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ABSTRACT

Phenomenology associated with effects of impressed acoustical fields upon flame propagation rates was studied with propane-air mixtures in open-ended tubes of 1.95 inches inside diameter. The sound source was a heating element located within the tube which established an acoustical resonance with the air column in the tube ("singing tube" phenomenon). Observed peaking of flame velocities was attributed to the presence of pressure loops associated with acoustical standing waves arising from the flame front itself and from the induced resonance.

Local increases (peaks) in flame velocity of a factor of two or three above baseline values were observed under the influence of the "singing", and these peaks corresponded to a narrow range of heater wattage. Under these conditions it is believed that reinforcement of the standing waves arising from the two acoustical sources occurred. These findings were used to correlate flame velocity data obtained with various tube geometries by other investigators.

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1.0 INTRODUCTION

1.1 GENERAL BACKGROUND

Effects of impressed acoustic waves upon momentum, mass and heat transfer processes have been observed and reported by a great number of investigators. Such effects are observed in systems containing liquid only, gas only, and two-phase mixtures of these. In gaseous systems these effects may arise from motion of the molecules in the acoustic modes, from recirculation cells formed as a result of interaction with vessel walls, or from other sources. Since propagation of flame through a tube filled with a combustible gas mixture involves a number of heat and mass transfer processes on both the local and the bulk level, it is reasonable to expect that some of these processes would be affected by the presence of impressed acoustic waves.

Significant effects also result from acoustic fields which are produced during the propagation or establishment of a flame front within a duct. Typical of these effects is the resonance present in jet engine combustion instability, or "screeching", which has been studied extensively because of its demonstrated threat to the integrity of engine components. These phenomena are related to the erratic behavior of flame fronts traveling in ducts which are partially or completely closed on one or both ends. It is generally accepted that such behavior, which can include attainment of very high propagation rates (and detonation), is strongly linked to the acoustic signals arising from the flame front itself.

Relatively little work has been directed toward the study of transient acoustic effects, or those arising from a short-term phenomenon such as flame propagation in tubes without high reactant flows, as opposed to steady-state effects such as "screech" in which standing waves are well established. Even less attention has been given to acoustical effects on transient combustion in completely open tubes, which was the field of interest for this program.

Knowledge of the phenomena which could occur during flame propagation through open-ended vent systems for aircraft fuel tankage, particularly with respect to effects of acoustic fields imposed by structural noise, lightning, the flame front, or other sources, is important to the assessment of hazards associated with such vent systems. Of particular interest is the exposure of conditions under which flame propagation rates in vent ducts could be accelerated toward a detonation velocity due to the presence of acoustic fields from the above-mentioned sources. It was the purpose of this research program to seek conditions under which significant increases of flame propagation rates (for hydrocarbon-air mixtures in open-ended tubes) could be produced by acoustic waves. A further objective was to determine the nature of the interactions causing such increases.

1.2 RECENT WORK

The most recent work on the specific problem of acoustical effects on transient propagation rates in tubes was presented by Laustsen(1) of the Boeing Company in a paper to the Combustion Institute (Western States Section), in which the effects of flame propagation rate upon the effectiveness of a certain type of flame arrestor material were determined. Laustsen anticipated that flame speed (propagation rate) in ducts would be highly sensitive to geometry. For instance, propagation in a pipe open at both ends would be essentially constant over the length of the experiment; but partially closing off one end of the tube would be expected to increase or decrease the propagation rate depending on the placement of the restriction (restriction upstream of the ignition source increases flame speed; restriction downstream of the ignition source decreases flame speed). These effects were expected as a result of expansion or compression as the flame propagates (again, depending on placement of the restriction).

However, in the experiments of Laustsen with restricted tubes, effects of much greater magnitude than those attributed to gas expansion were noted. In addition, the observed flame speeds were extremely erratic. On the basis of this and further work using impressed acoustical waves, Laustsen(1) reached several conclusions which are pertinent to this work:

(1) Flame propagation rates in tubes are strongly affected by acoustical vibrations generated by the presence of the flame;

(2) Enhancement of flame propagation rates by "organ pipe oscillations" is not propagated downstream of the zone of local pressure fluctuations;

(3) Knowledge of mechanisms whereby acoustical signals are generated by flame and whereby these signals affect the combustion process would be necessary for prediction of flame behavior at conditions under which such signals are present.

The results reported by Laustsen in Reference 1 will be discussed in detail in a subsequent section of this report.

1.3 OPEN-ENDED TUBES

The erratic behavior of flame speeds observed by Laustsen in tubes with partially or completely closed ends was not found to be present in completely open-ended tubes. This result indicated to us that the acoustical fields due to the presence of a flame front would not grossly affect the flame propagation rates in our studies with open tubes. As will be discussed later, however, our flame propagation rates as a function of position were strongly influenced by the flame-generated acoustic field. Nevertheless, our original assumption that erratic flame front behavior and non-reproducibility of propagation-rate data would be minimized through the use of open-ended tubes did appear to be justified based on the quality of the data obtained.

Both Spurlock(2) and Purdy(3) found discrete zones of recirculation within gas-filled, open-ended tubes subjected to an acoustic field. These zones, or cells, occur both with and without throughflow, but in the case of throughflow the cells are not continuous across the diameter of the tube; there is a center core of flow around which the cells form. Above some critical velocity (depending on the cell strength) the cells are literally "blown away" and do not become established. Cell strength, in turn, is dependent on the sound field, system geometry, and the nature of the heat transfer processes which occur in the tube. For the work in References 4 and 5, on which the analyses in References 2 and 3 are based, the outside of the tube was steam-heated, and the acoustic driver was located outside of the tube near the inlet.

Under the conditions imposed by both Spurlock(4) and Jackson(5), local wall heat transfer coefficients were greatly increased in the recirculation zones, corresponding to high local velocities in the cells. The velocity in the central core (the fraction of the gas undergoing net flow) is also higher than in the case of no sound field (at a constant mass input),simply due to the reduction of cross-sectional area for flow by the presence of recirculation cells. Thus, for an open-ended tube we expected flame propagation rates to be affected by the presence of any cells formed. These expectations were based upon anticipated high local velocities in the cells and also increased velocity of the central core due to the presence of the cells, so long as the conditions of sound field and flow rate are such that the recirculation cells exist.

1.4 THE SINGING TUBE

An acoustic field could be provided by a driver outside of or inside of the tube. In this program we chose to work with the driver in the form of a heat source inside the tube, so that coupling between the tube walls and the acoustic fields could be optimally established, and for convenience in conducting combustion experiments.

When a heat source of sufficient power is placed approximately one-fourth of the distance between the tube inlet and the outlet, and when a gas throughput is provided within a certain range, the tube and the gas column will resonate with a frequency dependent only upon the length of the tube. This phenomenon, commonly referred to as the "singing tube experiment", was first described by Rayleigh(6) as utilizing a flame for the heat source (heated wires work as well). Putnam(7) theoretically explained this phenomenon, and numerous other workers have used it to exemplify production of acoustical vibrations by a flame.

In the case of a vertical tube with the heating element "tuned" (located at the pressure node of the fundamental standing wave about one-fourth of the way up the tube) the convection current established by the heat input creates the throughflow and initiates the resonance, whereas in the case of a tube at an angle less than about 45° from the horizontal a forced throughflow must be supplied in order to establish the resonance. The latter case was the geometry used in this program.

1.5 PROGRAM OBJECTIVES

This research program had as its primary objective the determination of conditions under which flame propagation rates for gaseous hydrocarbon-air mixtures in open-ended tubes could be significantly increased through the action of acoustic waves. For this program the acoustic driver used to produce resonance of the air column in the tube was a heat source located within the tube (the "singing tube" phenomenon). It was expected that the phenomena observed would be more reproducible and less complex than flame propagation-rate data from closed-end or partially closed (orificed) tubes. A second objective of the program was to analyze and interpret the data obtained in order to obtain a better understanding of acoustical effects upon flame propagation in ducts.

2.0 EXPERIMENTAL METHODS AND RESULTS

2.1 SINGING TUBE EXPERIMENTS

A number of experiments were performed to study the "singing tube" phenomenon so that the apparatus to be used for the program could be designed to maximize both the sound pressure levels and the reproducibility of the flame propagation tests.

2.1.1 Properties of a "Singing Tube"

The tube used in these tests was a one-inch I.D. Pyrex pipe 18 inches long. The ends of the pipe were slightly rounded into grooved surfaces used for O-ring seals. The heat source was a flat spiral made of a one-foot length of Nichrome wire (30 mil diameter) formed to fit within the tube. The electric power to heat the wire was provided by a DC power supply equipped with an ammeter and a voltmeter.

Some rough exploratory measurements of temperature distributions within the tube were performed during near-minimum resonance (barely audible). In these tests the tube was horizontal, and air was fed into the tube inlet through a 0.25-inch diameter copper tube. Temperatures were measured with a thermometer. The heat-source produced tuned conditions when positioned approximately four inches from the tube entrance. At a power level of 56 watts and a flow rate (neglecting air pumped in by convection currents, etc.) of 0.45 cfm (STP), the temperature at the tube exit was 199°F. Upon inserting the thermometer into the tube, it was found that at a position two inches upstream of the tube exit the temperature rapidly increased, reading 223°F near the wall, 242°F at the centerline, and a maximum of 247°F at a point approximately halfway between the wall and the centerline.

These results indicated to us that recirculation cells might be present in the tube, ending one or two inches from the exit. The presence of the temperature dip at the centerline was believed to indicate a center core of flow.

Another series of experiments were performed at the same conditions of flow rate and heater power (barely audible resonance) to determine the effects of detuning the heat source. Although the temperatures observed were erratic, a typical effect of detuning the heat source by moving the wire coil about 0.1 inch toward the inlet was to increase the mean exit temperature of the air from 200°F to 225°F. We believe that this large change in exit temperature corresponds to strong thermal interaction with the tube walls when the heat source is "tuned" and poor heat transfer to the walls when "detuned". It should be noted here that it is necessary for a thermal gradient above some critical magnitude to exist between the heat source and the tube walls in order for resonance to occur under any conditions. When the outside wall of the tube was insulated, singing could not be established.

Under some conditions it is possible to significantly lower the heater temperature (cooling effect) and increase the throughflow by "tuning" the heater position to a resonant case in a vertical tube (mass flow by natural convection). Thus, the singing tube can also exhibit a pumping action in addition to enhancement of gas-wall interaction when resonance is present. This pumping action can occur with the tube in either the vertical or the horizontal position. Because of the pumping effect, gas throughflow must be introduced through a plenum in order that accurate measurement of throughput can be obtained. It was found that a flexible, spherical bag of three inches diameter would not serve in this capacity. However, a plastic distilled-water jug of 10-gal capacity appeared to serve very well as a plenum, for the particular tube used, without interference with the resonance.

2.1.2 Operating Ranges for Resonance

A plot of heater wattage versus theoretical gas velocity (throughput measured with a wet test meter at STP) upstream of the heater is presented as Figure 1, to characterize the interaction required between these two variables to produce resonance. The audible range of sound emanating from the tube is bounded by an apparent parabola with its origin at

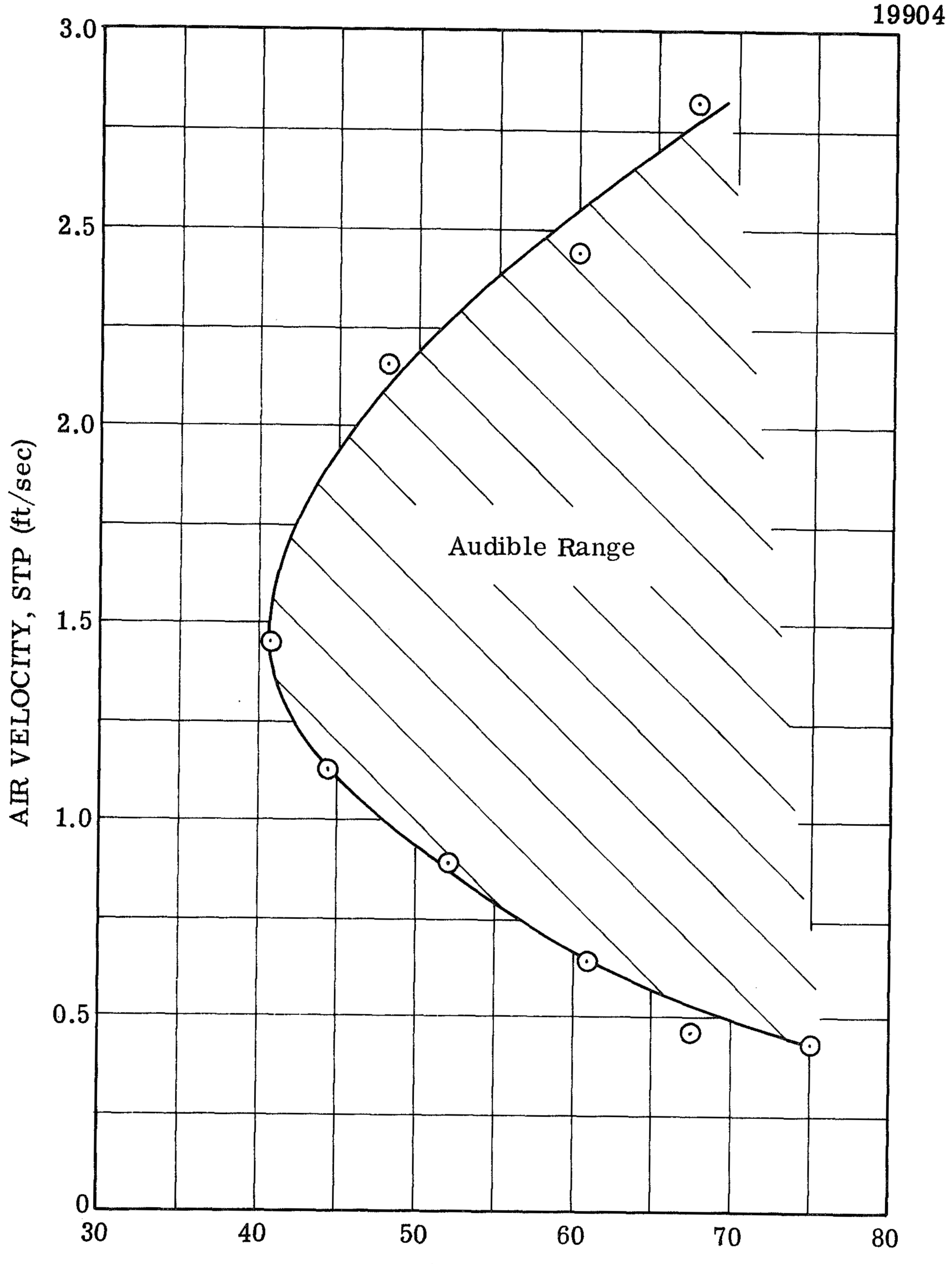

Figure 1. Velocity Limits of Audible Sound for 1-Inch I.D. × 18-Inch Long Vertical Glass Tube with Nichrome Coil Heater Located at L/4.

approximately 40 watts and 1.4 to 1.5 ft/sec gas velocity. As flow rate is slowly increased from zero at a given heater wattage (over 40 watts) it is evident from Figure 1 that the zone of audible sound is entered, crossed and exited from.

The variation in sound amplitude with air velocity was studied with a microphone connected into an oscilloscope. This function is presented in Figure 2. As the air velocity was increased the resonant frequency became observable on the oscilloscope screen at about 0.28 ft/sec and audible at about 0.35 ft/sec air velocity. Over this region amplitude appeared to be a fairly strong function of air velocity, but not nearly so strong as the relationship observed at values of air velocity above 0.4 ft/sec. A tailing off of the amplitude at air velocities above 2.77 ft/sec could not be observed, perhaps because of the noise arising from the throughflow. The 330 cps frequency and the wave shape were very pure except at the highest values of air velocities used.

Thus far, the presence of the "knee" at slightly over 0.4 ft/sec on Figure 2 cannot be fully explained. It is possible that two distinct types of interactions occur between the tube wall and the air column, each type giving rise to the same resonant frequency but each also producing very different amplitude functions. It appears more likely that the "critical" velocities of about 0.42 ft/sec and 2.77 ft/sec represent the limits of cell strength (for recirculation cells to exist) as a function of air velocity, and that the low velocity "tail" on Figure 2 represents some type of resonant coupling without the presence of recirculation cells.

2.1.3 Studies of Particle Mechanics in a Singing Tube

Based on the results of the preliminary studies reported in Sections 2.1.1 and 2.1.2, it appeared that a better understanding of phenomena associated with the singing tube would be necessary both for the interpretation of the propagation rate data from the program and to any effort to any effort to express analytically the flow geometry in the tube. Thus, a

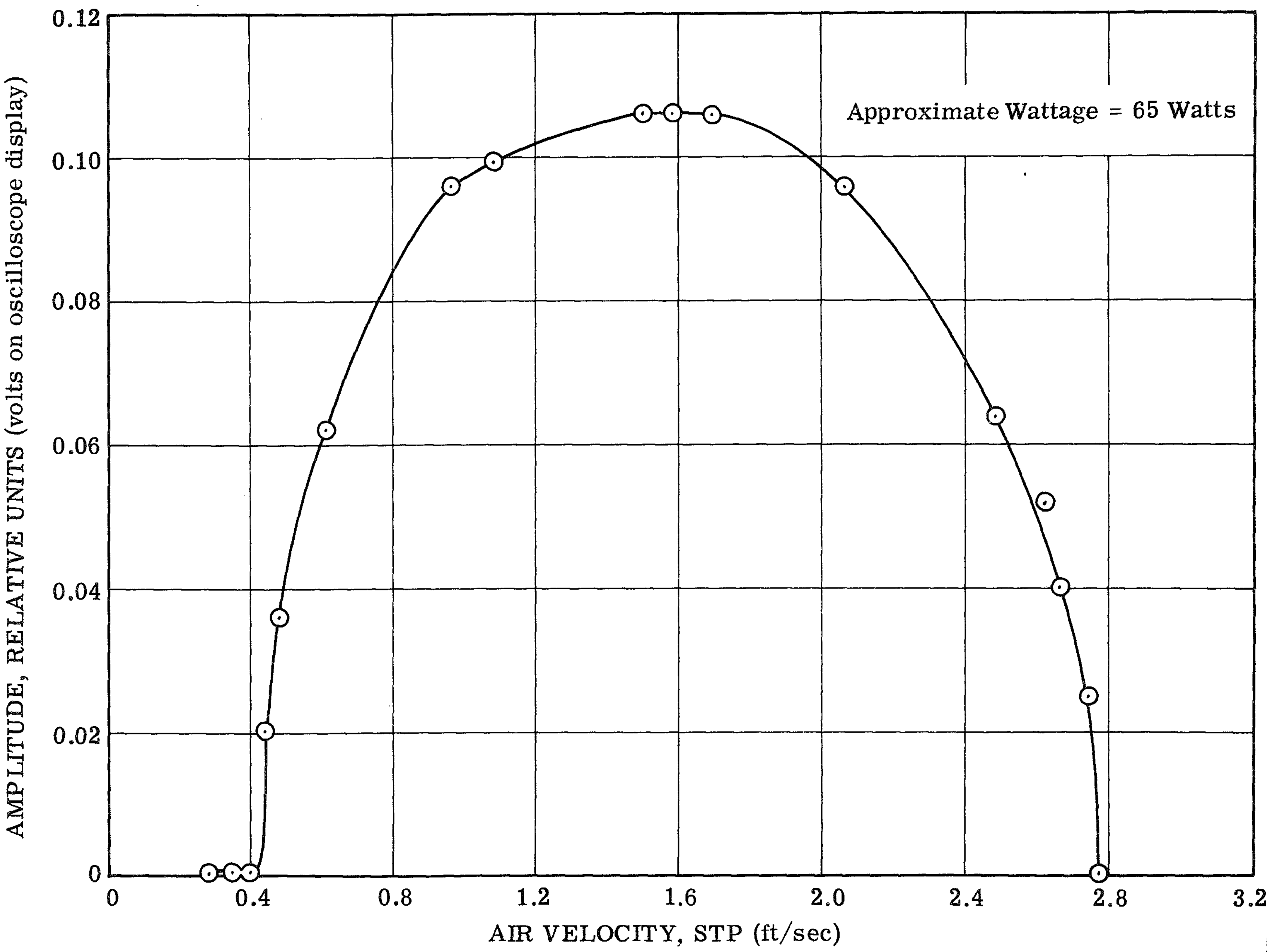

Figure 2. Amplitude of Resonance Versus Air Velocity at STP for a 1-Inch I.D. × 18-Inch Long Singing Tube with a Wire Coil Heater Located at L/4.

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small effort was expended towards obtaining visual definition of the flow behavior within a singing tube. The use of smoke particles was soon found to be of no value in this study due to the center streaming which occurred. Smoke introduced at the tube entrance simply streamed down the center of the tube and exhibited no tendency to recirculate. Smoke particles introduced prior to the establishment of singing were swept from the tube before singing could be initiated. Small tubes delivering smoke to various portions of the tube upstream of the heater disturbed the resonance, stopping it completely in some cases. These types of problems have been encountered in previous attempts to use bulk smoke for flow visualization. Although a highly sophisticated method of smoke introduction could probably be devised to work in the singing tube, the effort in this direction appeared to be outside the scope of this program.

Limited success in defining the presence of recirculatory cells was obtained with small particles placed in the tube prior to establishment of resonance. Colloidal silica particles of very small diameter proved to be the best material for use in these studies. In a horizontal singing tube, with gas throughput provided by a stream of Freon from a pressurized bottle, the colloidal silica particles piled up at regularly spaced intervals over approximately the last 25 to 30 per cent of the tube length. These piles, perhaps corresponding to the position of nodes of standing waves, are completely analogous to those seen in a Kundt's tube experiment.

The presence of the particle piles over the last 25 to 30 per cent of the tube length is interpreted as a strong indication of small (short) recirculatory flow cells along this length, and the absence of particle piles over the upstream length could correspond to the presence of a longer recirculatory flow cell (or a pair of longer and stronger cells) along this portion of the tube. These cells are visualized as being very near the tube wall with a general positioning as shown in Figure 3.

With the singing tube mounted vertically, studies were made of the action of colloidal silica particles (agglomerates) resulting from

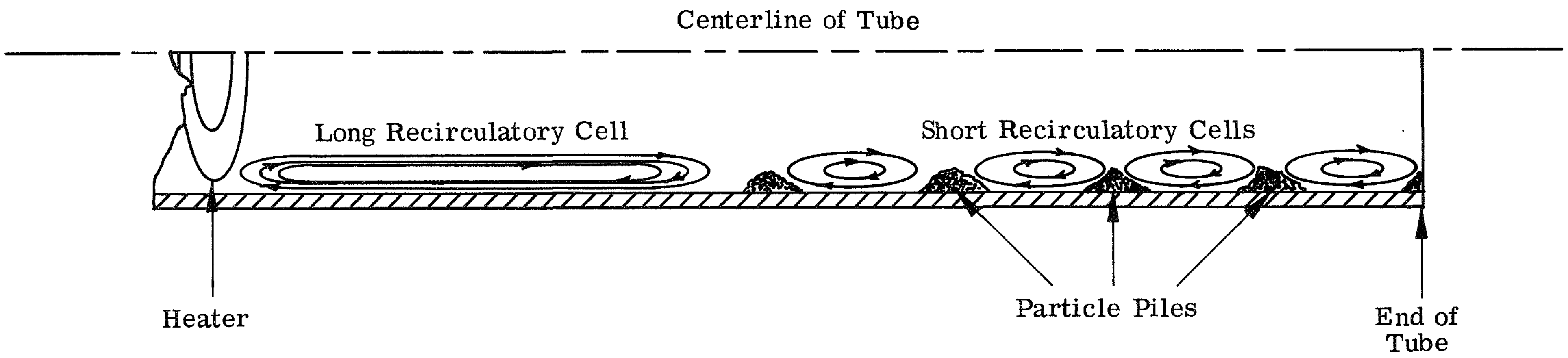

Figure 3. Sketch of Hypothesized Recirculatory Cell Formation in Singing Tube (Positions of Particle Piles During Singing also Shown).

introduction of the particles into the tube both from above and from below. Some particles in the neighborhood of the heater were carried upward by thermal currents, and these returned to the heater rather slowly upon cooling. This activity occurred mostly near the interior of the tube (away from the walls). Other particles near the walls were observed to move swiftly upwards and then just as rapidly downward. It is these particles which are believed to have been entrained in recirculatory cells. Although the approximate thickness of these hypothesized cells could not be estimated from the observed particle motion, their upward travel occurred within a few millimeters of the wall and their downward travel occurred seemingly almost in contact with the wall. The particles reversed direction very near the heater and again at a variable distance up the tube. Some particles traveled to within a few inches of the top end of the tube before reversing direction, but most reversed direction prior to reaching 75 per cent of the tube length.

2.2 EXPERIMENTAL PROCEDURES

2.2.1 Main Experimental System

A single duct diameter of two inch nominal (1.95 in. actual inside diameter), schedule 80 black iron pipe was used in the main test system of the program. Two lengths of pipe, 36 in. and 56 in., were used. The experimental system consisted of a large steel plenum, through which the air flow was introduced into the pipe, and the instrumented pipe screwed into the plenum, plus associated control, regulation, and recording equipment. The instrumented 36 in. pipe is shown in Figure 4. Pressure transducers (0-50 psig) were installed both in the tube and the plenum. These transducers did not indicate any pressure change during combustion, and a 0-5 psig transducer mounted in the tube in place of the 0-50 psig transducer also failed to detect any pressure change during combustion. Excitation for the transducers was supplied by signal conditioning modules which also upgraded the transducer output signals for recording on an oscillograph. It is recognized that the frequency response of these transducers would not have

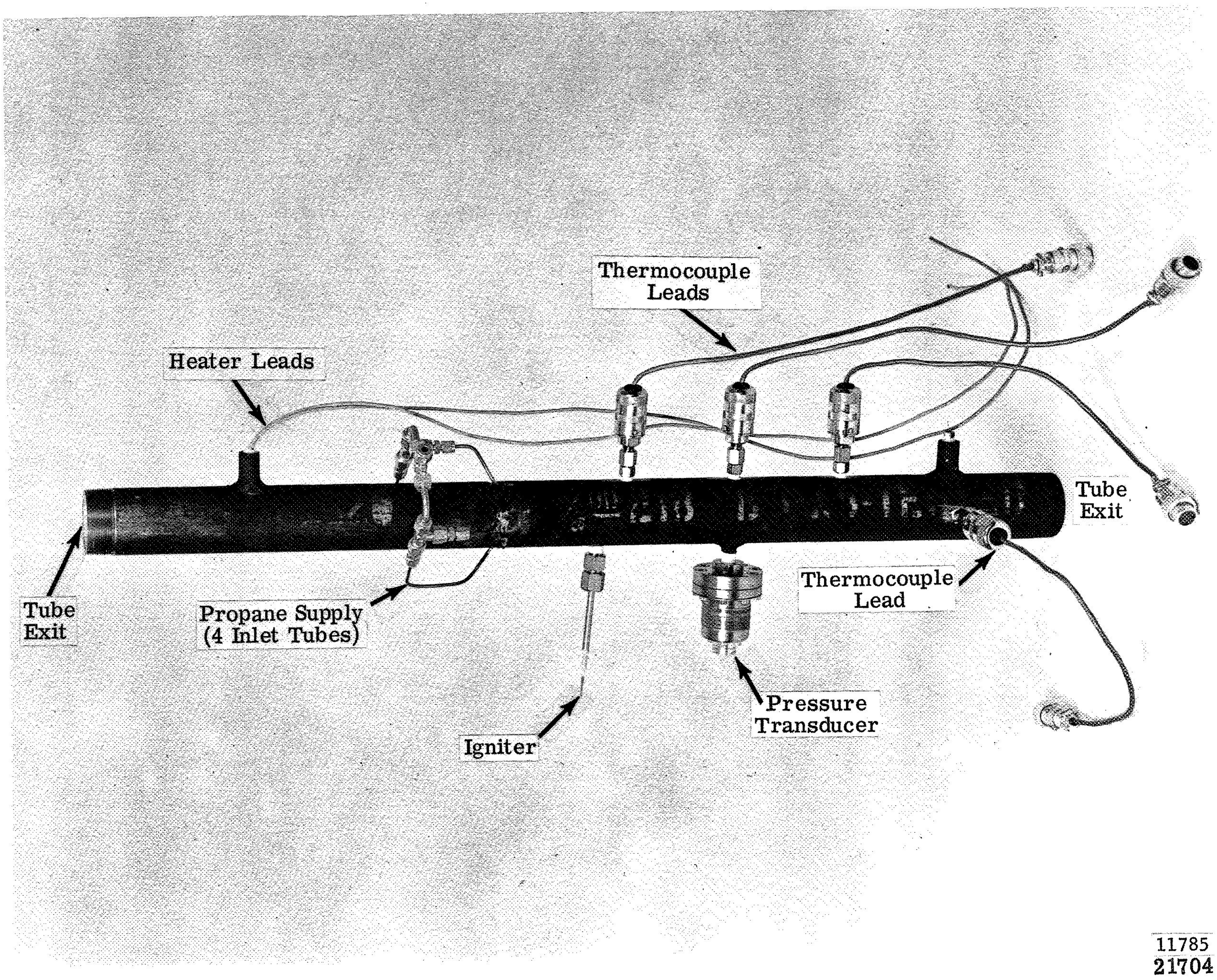

Figure 4. Instrumental 36-Inch Tube (Schedule 80 Black Iron Pipe).

been sufficient to pick up oscillatory pressures resulting from the singing and the combustion. The intended use of the transducers was to pick up any overpressures due to the combustion.

The thermocouples were 5-mil chromel-alumel with an ambient reference (exact knowledge of flame temperatures proved to be unimportant to the program). Voltage signals from the thermocouples were fed into signal conditioners, from there to amplifiers, and then into the galvanometers of the recording oscillograph. The frequency response of the galvanometers was flat ± 5 per cent up to 1,000 cps, and that of the amplifiers was flat up to 2,000 cps or higher. Thermocouple spacings were 4 in. for the 36-in. tube and 4.25 in. for the 56-in. tube. Four thermocouples were installed in the shorter tube and seven in the longer tube.

The igniter consisted of a spark gap from a central rod to a grounded stainless steel sheath across alumina insulation. The power source was a 6 kv neon ignition transformer. The distance between the igniter and the first thermocouple (both located at the center of the tube) was one inch. Propane was introduced through four tubes (0.125 in. o.d., 0.030 in. wall) located approximately 4 in. upstream of the igniter. As shown in Figure 4, a common supply tube fed all four jets. The 0.125-in. tubes extended into the tube about 0.5 in. at a 45° angle from the horizontal. This arrangement was used because of the very limited mixing distance available, and excellent agreement between propagation rate data with thermocouples located at the center and thermocouples located 0.25 in. from the wall has indicated that adequate mixing was obtained.

The heater which served as the sound source was located approximately one-fifth of the way down the pipe, but the exact location was variable over a distance of three or four inches. No problem of the heater igniting the propane-air mixture was encountered. The interior of the pipe was coated with a high-temperature cement over the length where the heater was to be located in order to provide electrical insulation between the heater and the pipe. Although several types of heaters were used, most designs consisted of a coil of nichrome wire around a helical insulator. The insulator provided shape stability at high temperature, and both silica rods and metal rods coated with insulating cement were used for this purpose. It was found that the 56 in. tube would resonate only with a coated-metal rod insulator (not with a silica rod).

A microphone connected to a sound level meter (140 db maximum) was placed near the tube exit. This equipment served both to determine the sound level of the background and the resonance and also to record the resonance through the oscillograph. Normal background ranged from 80 to about 90 db, and the maximum resonance sound level attained was about 120 db. The "C" weighting scale of the db meter was used throughout the program.

The assembled experimental system was mounted out-of-doors to minimize hazards from the use of the propane in a necessarily unconfined space. A photograph of the system is shown in Figure 5. The high background noise level was due to nearby facilities utilizing steam ejection for high altitude and space simulation. The tests were performed from behind a plywood panel board protected by sandbags. Instrumentation lines were run from the site into the High Altitude Facility data acquisition room in which were located the signal conditioning and recording equipment.

The control equipment, rotameters, switches, valves, and compressed gas cylinders were all mounted on the plywood control board. A watt meter (maximum 750 watts) was also mounted on the board to facilitate the testing at various heater wattages. Rotameters for the measurement of air and propane flow rates were equipped with thermocouples and manometer connections to allow accurate flow-rate determinations. The basic calibration of the flow control system was performed with a wet-test meter under conditions exactly similar to a normal test.

Experimentation with the assembled apparatus (plenum plus instrumented 36-in. pipe) revealed that an air flow rate of 1.3 cfm (50°F) would produce strong resonance at heater wattages above about 150 watts and weak singing at 125 watts. This value of air flow rate, which was used for

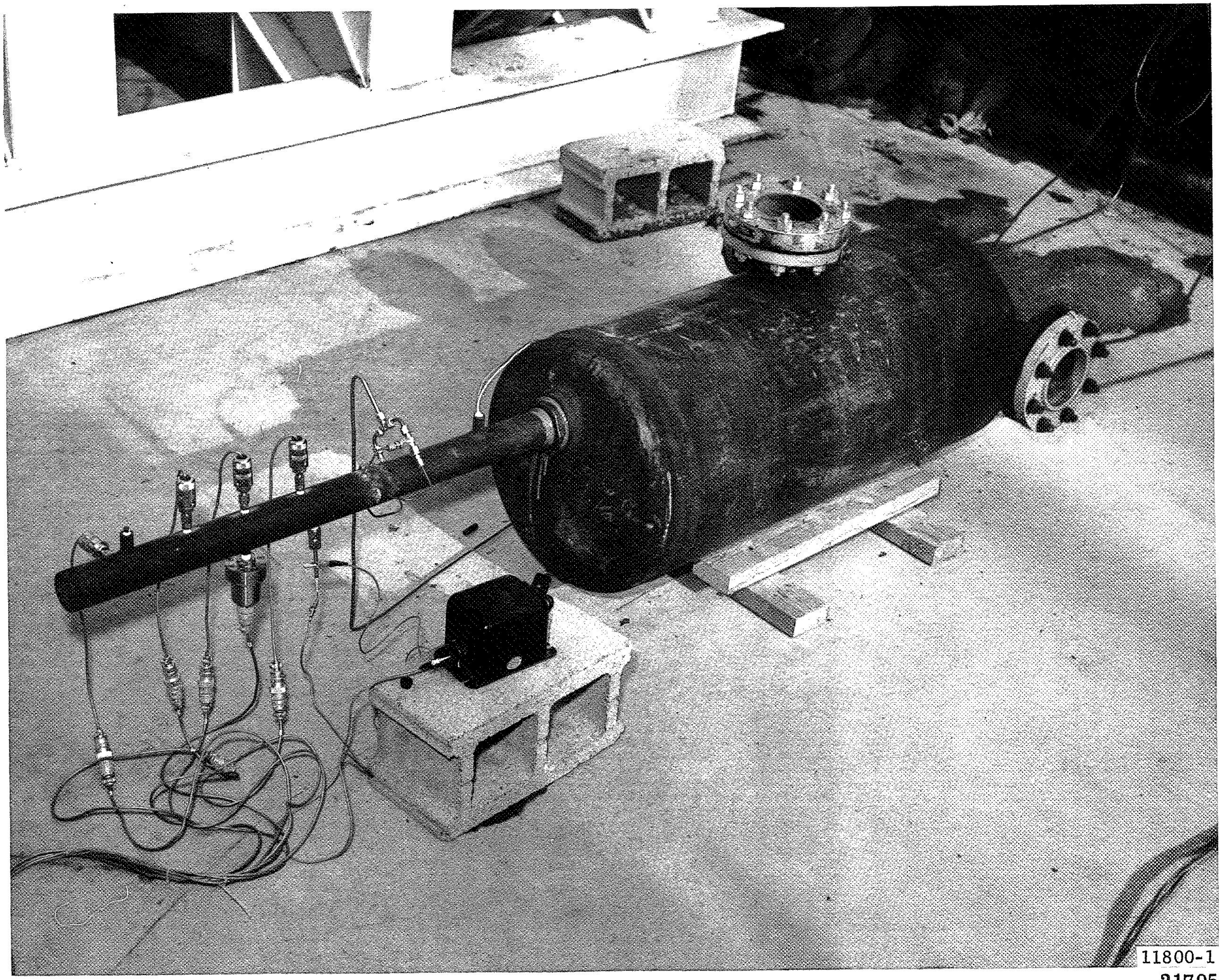

Figure 5. Instrumented 36-Inch Tube Attached to Plenum.

all testing under the program, corresponds to a linear velocity of about one ft/sec through the pipe. Two propane flow rates were used in the program, corresponding to 2.0 per cent and 4.0 per cent of the mixture. The latter mixture represents an approximately stoichiometric mixture of propane with air. The overall Reynolds number in the pipe was on the order of 1,000 for all of the experimental work.

2.2.2 Test Procedures and Data Handling

Test procedures were generally as described below:

(1) Set propane and air flow rates at proper values and allow to flow for at least 30 seconds prior to each test;

(2) Check background noise level on db meter;

(3) Set heater wattage at desired value;

(4) Communicate with data recording room and, if OK is obtained, proceed with countdown;

(5) At count of "one" recorder is switched on;

(6) At "go", igniter switch is actuated and left on approximately three seconds;

(7) Propane solenoid valve is closed as soon as possible after ignition switch is actuated;

(8) Recorder is turned off when all thermocouple traces have been observed to deflect.

The thermocouples were calibrated electronically at the beginning of each day of testing. This was more to insure correct operation than to obtain accurate flame-front temperatures. Flame propagation rates were calculated from a measurement of distance between points of initial rise as compared with timing lines displayed on the oscillograph trace.

2.3 DATA AND RESULTS

2.3.1 Data Properties

A total of 266 individual tests were performed, from which about 1,000 usable flame propagation rates were obtained. The data are reported herein for a number of discrete series of tests, because of the variations inherent in both flame propagation rates and the nature of the acoustical resonance due to variations in ambient temperature and wind conditions. Also, several heaters were burned out during testing, and there appeared to be slight variations in the acoustical resonance as a result of differences between heater geometry and placement in the tube.

Flame propagation rates were calculated from the distance between initial temperature rise points on the oscillographic trace moving at a known rate. The presence of timing lines on the traces added to the ease and accuracy of determining the initial rise points. In most cases the thermocouple rise points were obvious, but in a number of tests (particularly those in which the leaner of the two mixtures was used) some subjective interpretation of the traces was necessary to obtain propagation rates. Also, for a number of tests with the lean mixture, and for a few with the approximately stoichiometric mixture, the thermocouples located furthest downstream did not indicate passage of a flame front. When these conditions occurred the upstream propagation rates were used even though no values were available from the downstream thermocouples.

We feel that the vast majority of the calculated propagation rates were accurate to well within ± 10 per cent, but that the error might have increased to ± 25 per cent in a few tests. However, none of the data reported herein fall into the latter category. Most of this error arose from difficulty in choosing initial rise points.

2.3.2 Peaking of Propagation Rate Due to Acoustical Field

One of the most striking results from the program was the occurrence of significant "spikes" of high propagation rates over a fairly narrow range of heater wattage. These are presented in Figure 6 for the 36-in. tube and in Figure 7 for the 56-in. tube. The high propagation rates, roughly a factor of two or three times greater than the maximum rates for the "no-singing" tests, occurred at 350 to 400 watts of heater power. In these tests, singing began at about 125 to 150 watts and increased in sound level approximately proportionally as wattage was increased. The maximum sound levels for Figures 4 and 5 were about 105 db and 118 db, respectively. In these data, and in fact in all data generated from the tests, no substantial effect of wattage due to heating of the air-propane mixture was observed; it appears that the only effect due to the heater was caused by the acoustical field it generated.

For the rich-mixture case in Figure 7, it is suggested that the extraordinary high value at zero wattage might have been an artifact. The next highest value obtained at that condition was 35.4 ft/sec. However, the propagation rates at zero wattage in this test series were generally higher than those at 100, 150 and 250 watts. The data in Figures 4 and 5 represent individual series of tests performed on the same day, since atmospheric conditions were believed to affect the test results for experiments with singing.

Attempts to reproduce the peaks shown on Figures 6 and 7, during duplicate tests at zero and 350 watts to the heater, showed that the high values did not occur during each test. Out of five duplicate tests (in addition to those associated with Figures 6 and 7) with the lean mixture in the 36-in. tube (three measured rates from each test) at both zero and 350 watts, peaks occurred in two. In comparison to a maximum rate of 14.1 ft/sec at zero wattage, the two highest maximum rates at 350 watts were 19.1 ft/sec and 27.0 ft/sec. It is probable that the peaks were present in other tests but the relatively small number of thermocouples used prevented their observation.

Another general trend observed in the data was the depression of flame propagation rates both upstream and downstream of the thermocouple positions between which the maximum peak values were obtained. This

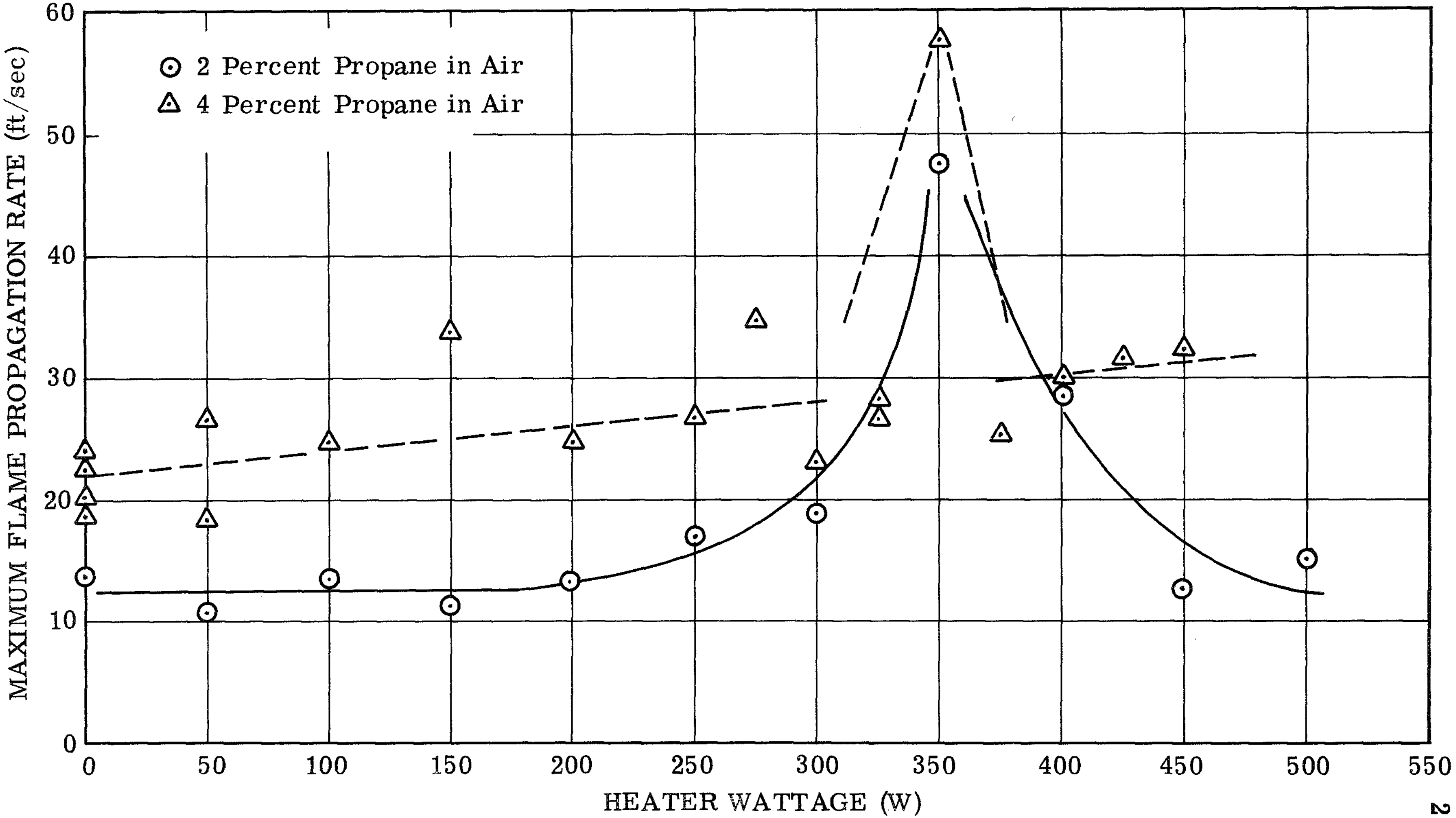

Figure 6. Plot of Maximum Values of Flame Propagation Rate with 2 and 4 Percent Propane and Air in a 36-inch Singing Tube as a Function of Heater Wattage (Tube Diameter 1.95 in.).

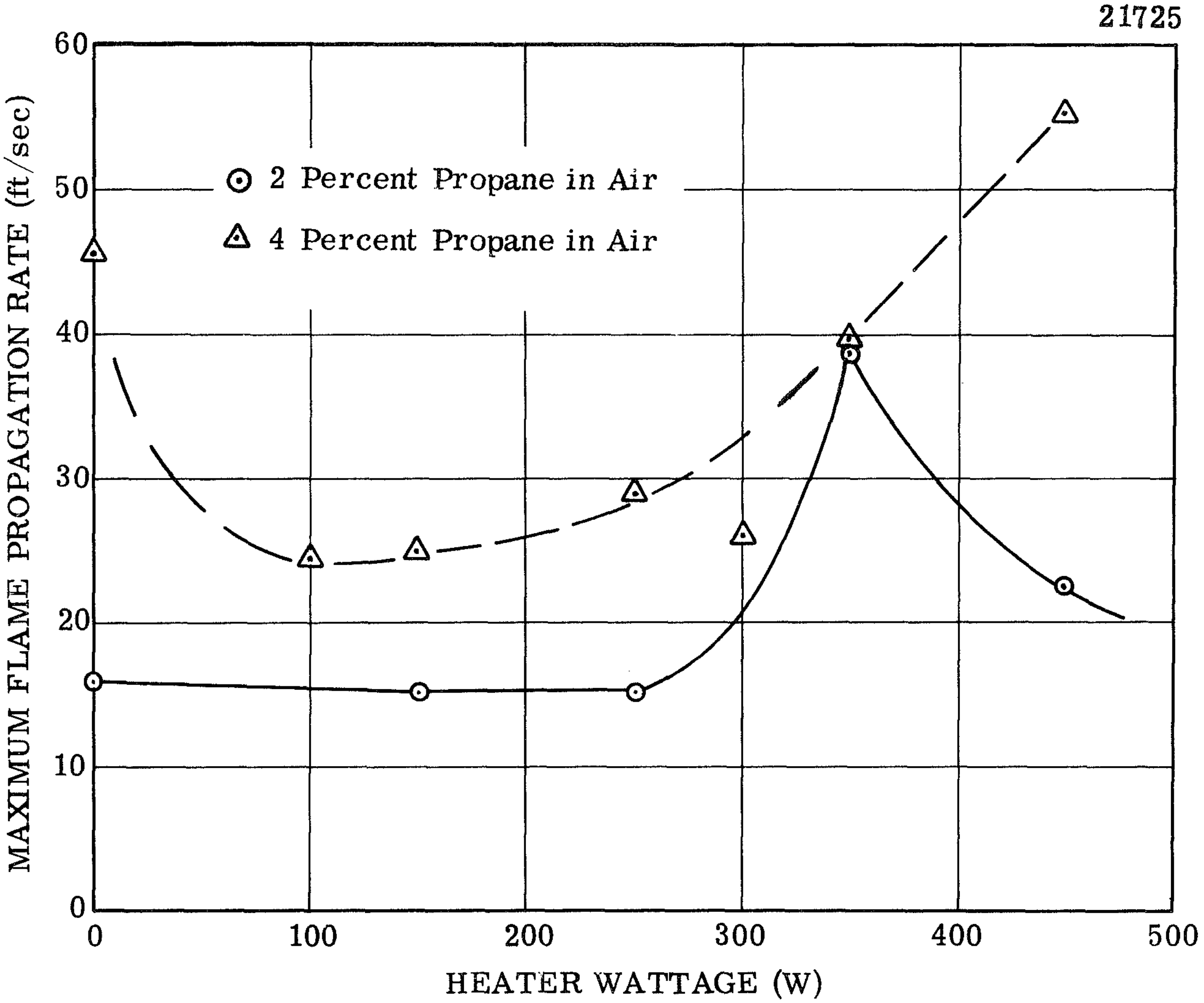

Figure 7. Plot of Maximum Values of Flame Propagation Rate for 2 and 4 Percent Propane and Air in a 56-inch Singing Tube as a Function of Heater Wattage (Tube Diameter 1.95 in.).

behavior is typified by the data on Table I. A plot of the maximum and minimum propagation rates obtained as a function of wattage for the test series of Table I is shown in Figure 8. These results show that the acoustical field from the heater is capable of both decreasing and augmenting the flame propagation rate, depending on the location of the sensors and the heater wattage. The data on Table I for zero, 50 and 100 watts to the heater may be taken as typical as to the relative scatter obtained without singing.

In some test series consisting of traverses of heater wattage from zero to as high as 650 watts, other peaks besides the usual one at 350 watts were observed. For instance, in the series presented in Table II (a separate series from others described heretofore) there is a slight peaking at 200, 350, and 600 watts. Several other peaks occurred at 600 or 650 watts besides these. These will be mentioned during discussion of their respective test series.

2.3.3 Effects of Resonance Sound Level

A number of test series were conducted to ascertain the effect of the sound pressure level upon the flame propagation rates, all other conditions being equal. The first such series consisted of a comparison between flame propagation rates at zero heater wattage and at 350 watts with the heater at two positions (0.20 L and 0.22 L, where L = 36 in). The sound level of the resonance was qualitatively stronger by a considerable amount with the heater at 2.50 L than with the heater at 0.22L. Fifteen tests were performed at each condition (zero watts, 350 watts with heater at 0.2 L, and 350 watts with heater at 0.22 L), using 4 per cent propane in air. This, therefore, was essentially a study of the effect of slightly detuning the heater with respect to the resonance at 175 cps (also the fundamental frequency of the tube).

The data from this series of tests were markedly free from peaks such as those shown in Figures 6 and 7, perhaps due to the use of slightly different heater design, contrasted with previous tests. It should be

TABLE I

Propagation Rate Data for 36 in. Tube (Air with 2 Per Cent by Weight Propane Flowing at 1 ft/sec)

Test No.	Heater Wattage	Propagation Rates, ft/sec Tc1-2*	Tc2-3*	Tc3-4*	Singing
44	0	13.6	8.0	6.9	No
45	50	7.7	10.8	7.9	No
46	100	10.8	13.6	8.3	No
47	150	6.7	11.9	6.5	Slight
48	200	13.1	13.6	9.7	Yes
49	250	10.7	17.1	7.2	Yes
50	300	12.8	19.0	8.8	Yes
51	350	10.5	47.6	5.4	Yes
52	400	2.9	29.0	3.1	Yes
53	450	1.9	12.6	8.0	Yes
54	500	10.7	15.1	9.7	Yes

---

* The thermocouples, spaced 4 in. apart, covered approximately the downstream half of the tube length except for the several inches at the end of the tube.

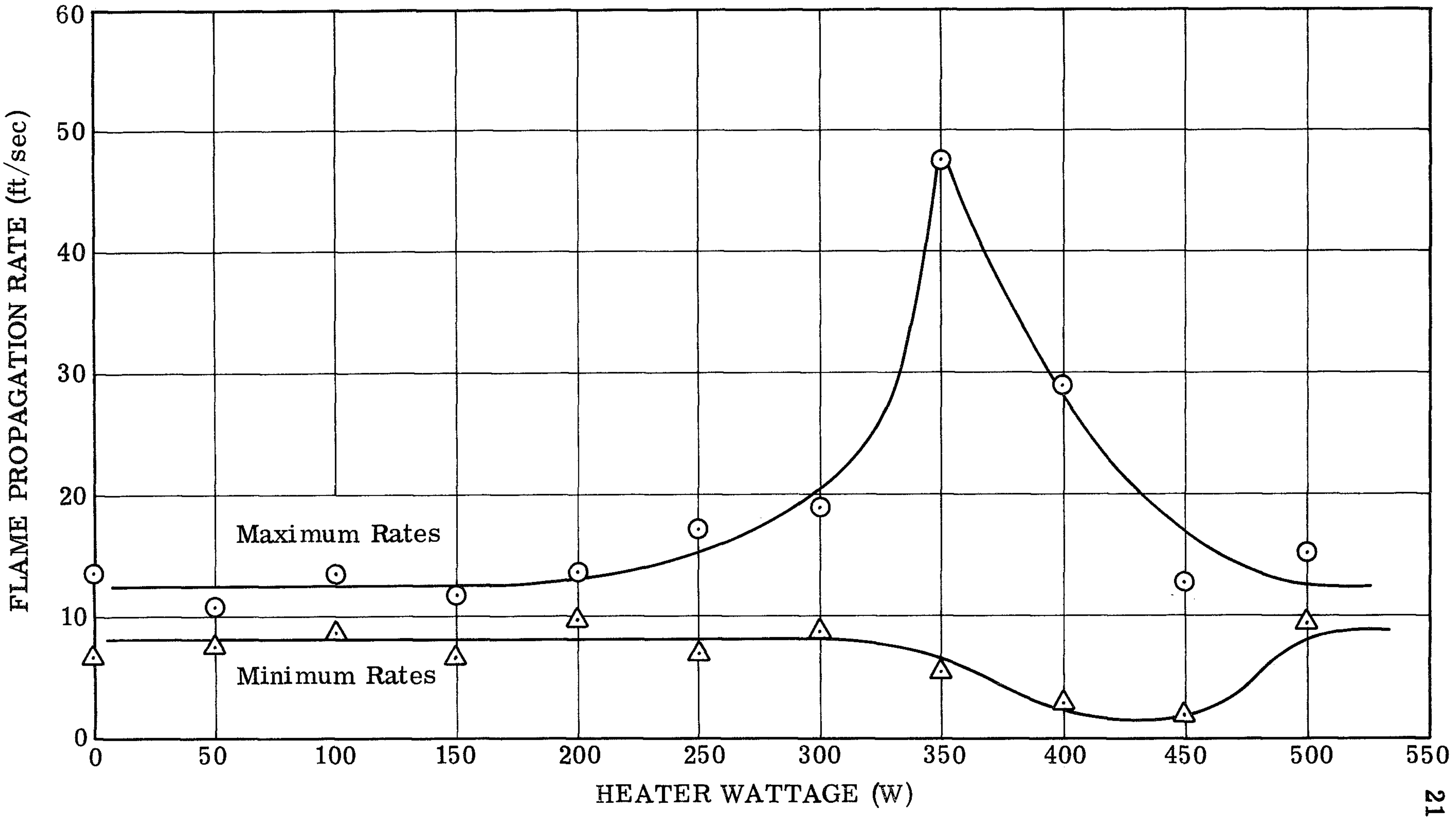

Figure 8. Plot of Maximum and Minimum Flame Propagation Rate with 2 Percent Propane and Air in a 36-inch Singing Tube as a Function of Heater Wattage (Tube Diameter 1.95 in.).

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TABLE II

Results of Test Series Showing Effect of Heater Wattage on Flame Propagation Rates for 4 per cent Propane in Air Flowing through a 2-in. Pipe 36-in. Long

Test No.	Heater Wattage (watts)	Maximum Flame Propagation Rate[a] (ft/sec)	Average Flame Propagation Rate[b] (ft/sec)
82	0	13.9	11.9
83	50	12.8	10.7
84	100	8.9	8.7
85	150	8.6	8.1
86	200	19.6	12.9
87	250	9.0	8.3
88	300	10.7	10.6
89	350	16.2	11.8
90	400	10.1	9.1
91	450	11.1	8.9
92	500	10.7	10.1
93	550	10.6	10.2
95	600	20.0	16.0

---

[a] Highest values obtained for specified conditions

[b] Average of three points

repeated here that the relatively large (4 in.) spacing between thermocouples could easily have missed such peaks if some characteristics of the tube which affected the position of these peaks were slightly altered. A summary of the data from this test series is presented as Table III. According to Table III a substantial increase in resonance sound level resulted in only a slight increase in propagation rates.

With the addition of the sound level meter mounted near the exit of the tube it became possible to compare relative db levels of the resonance at various wattages. As shown by the data in Table IV, the db level at the meter for the 36-in. tube was approximately a linear function of the heater wattage at values of wattage above about 250 watts (where strong singing was initiated). A significant propagation rate peak of 83 ft/sec occurred in this series at 600 watts, which was the highest propagation rate measured during the entire program. However, it should be noted that all of the propagation rate values in Table IV are somewhat high compared to the data in Figures 6 and 7. The mixture used in this series was 4 per cent propane in air.

Since it was known from laboratory work with the glass singing tube that small tubes inserted in the downstream end could strongly affect the sound level, it was decided to ascertain what effect this procedure (e.g., varying sound level at constant heater wattage) would have on propagation rates in the 36-in. tube. The gas mixture used in this series was 2 per cent propane in air. Test results, shown in Table V, reveal that there was essentially no dependence of flame propagation on the reduction of resonant db level produced by inserting a 1/4-in. O.D. copper tube into the 2 in. pipe, once the tube is inserted far enough to affect the singing.

However, the insertion of a tube would be expected to have a completely different effect on the flow behavior in certain portions of the pipe as compared to altering the tuning by shifting heater location. Based on the data in Tables III, IV, and V, then, we can say that the effect of varying only the resonant sound level on flame propagation rate is relatively

TABLE III

Summary of Test Data Showing Variations Due to Resonance Detuning from Studies of Acoustical Resonance Effects on Flame Propagation Rates of 4 per cent Propane in Air Flowing through a 2-in. Pipe 36-in. Long

Heater Wattage (watts)	Quality of Resonance	Position of Heater	Average Propagation Rate (Ave. of 15 Points) (ft/sec)	Maximum Propagation Rate[a] (ft/sec)	Minimum Propagation Rate[b] (ft/sec)
0	No Resonance	0.22 L	18.5	24.2	14.5
350	Weak Singing (Heater Detuned)	0.22 L	21.6	30.8	17.1
350	Strong Singing	0.22 L	24.6	32.4	18.6

---

[a] Highest values obtained at specified conditions

[B] Lowest values obtained at specified conditions

TABLE IV

Results of Test Series on Flame Propagation Rates in 4 per cent Propane in Air Flowing through a 2-in Pipe 36-in. Long, Showing Variation of Resonant Sound Pressure Level as a Function of Heater Wattage

Heater Wattage (watts)	Maximum Flame Propagation Rate[a] (ft/sec)	Average Flame Propagation Rate (ft/sec)	No. of Data Points	Sound Pressure Level at Tube Exit (db)
0	35	23.8	6	85-90[b]
50	55	25.0	6	85-90[b]
150	51	25.8	3	100
250	33	25.1	6	106
350	37	23.3	6	107
450	45	24.5	3	107.5
550	32	24.0	3	108.5
650	83	35.5	3	109.5

---

[a] Highest values obtained at specified conditions

[b] Background

TABLE V

Effect of Resonant Sound Pressure Level on Flame Propagation Rates of 4 per cent Propane in Air Flowing through a 2-in. Pipe 36-in. Long with a Constant Heater Wattage of 350 watts - Detuning by Insertion of 1/4-in.Copper Tube into Downstream end of Pipe

Test No.	Highest Observed Flame Propagation Rate (ft/sec)	Average Flame Propagation Rate (ft/sec)	Sound Pressure Level at Tube Exit (db)
100	15.2	11.5	88
99	13.6	12.2	90
96	13.9	10.3	92
105	9.5	8.2	94
104	13.9	11.0	95.5
106	11.6	11.2	96.5
97	12.6	11.8	97
103	10.1	10.0	97
102	9.9	9.7	98.8
98	7.4	6.9	99
101	10.4	10.1	100
95	13.1	10.1	100.3
89	16.2	11.8	102.5

slight, except under those conditions where peaking of the propagation rate occurs. The increases in flame propagation rate due to increased db levels (up to the maximum) at a constant heater wattage of 350 watts ranged up to about 40 per cent as compared with the factor of two or three resulting from the cases where peaking occurred.

2.3.4 Variation of Flame Propagation Rate with Distance from Igniter.

Under conditions of no (or only weak) singing there was essentially no variation of flame propagation velocities through the shorter (36-in.) pipe for either mixture ratio used. As was noted in Section 2.3.1, however, significant variation of flame propagation rate with distance from the igniter occurred at heater wattages above about 250 watts. This behavior is typified by the data in Table I, although in most other tests using similar conditions (two per cent propane in air) the peaking between the second and third thermocouples was not as pronounced as that in Table I. In addition, such peaking of propagation rates was somewhat less pronounced with a 4 per cent propane/air mixture than with the leaner mixture. Nevertheless, this variation of propagation rates between successive thermocouple positions was generally present when the resonance (singing) was well established, and was most apparent under conditions at which strong peaking occurred at about 350 watts.

In the longer (56-in.) pipe, variation of flame propagation rates as a function of distance from the igniter at conditions of zero heater wattage (no singing) was observed. This variation occurred as a peaking at two of the measurement locations in a manner somewhat similar to that observed by Laustsen(1), except that in the present work the peaking was less pronounced and could not be considered erratic in the least. The propagation rate data for these tests are presented in Table VI, and the average values are plotted in graphical form in Figure 9.

TABLE VI

Flame Propagation Rates at Various Distances from Ignition for a Mixture of 4 per cent Propane in Air Flowing in a 2-in. Pipe 56-in. Long (No Acoustical Resonance)

	Flame Propagation Rate between Designated Thermocouple Locations (ft/sec)					
Test No.	Tc_{1-2}	Tc_{2-3}	Tc_{3-4}	Tc_{4-5}	Tc_{5-6}	Tc_{6-7}
181	14.2	22.8	31.5	24.0	20.0	----
183	15.9	23.5	26.1	23.0	28.8	20.6
200	15.4	26.6	28.1	23.8	32.2	22.7
201	16.9	23.4	30.8	24.6	39.4	28.1
202	18.5	20.3	26.6	26.6	46.8	32.2
205	17.2	20.2	32.2	21.2	33.7	18.0
Average	16.4	22.8	29.2	23.9	33.5	24.3

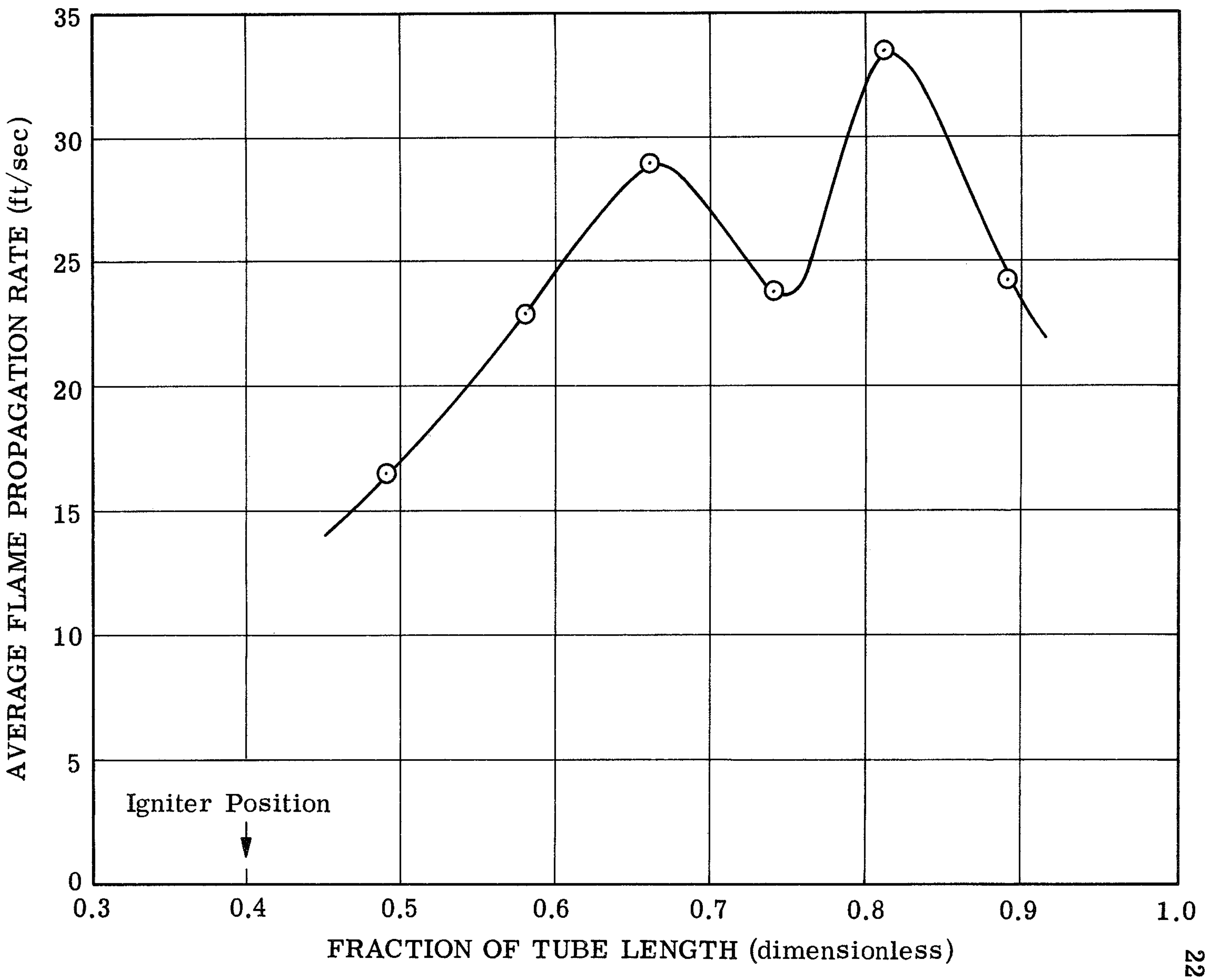

Figure 9. Variation of Flame Propagation Rates for 4 Percent Propane in Air with Distance from Igniter Position for a 2-Inch Pipe 56-Inches Long.

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The series of which the data in Table VI was a part was concluded by tests using 200, 400, and 600 watts of heater power in order to ascertain the effect of the resonance strength on the data trend shown in Figure 9. The 350-watt value was not used here in an attempt to avoid strong peaking associated with this particular wattage. The averaged results of the entire series are summarized in Table VII. Although the individual values of flame propagation rates obtained for the tests with wattage are not included, their variation was very similar to that of the values in Table VI.

The data in Table VII show that, as the heater wattage (and resonance sound level) was increased, the degree of peaking was first decreased (at 200 watts), then was increased (at 400 watts), and at 600 watts there was only one peak. In addition, the values of flame propagation rate between thermocouples 1 and 2 and between thermocouples 2 and 3 exhibited steady increases as the heater wattage was increased. The propagation rates near the tube exit (thermocouples 6 and 7) closely followed the values obtained between the two stations immediately upstream. As will be discussed later in this report, we believe that these findings are very revealing as to the nature of the acoustical interactions with flame propagation which occurred throughout this program.

Tests were also performed with the upstream end of the 56-in. pipe closed off by a rubber stopper (except for the air feed line) in one case, and in another case completely open in order to determine, if possible, the effects of the plenum on the upstream end of the pipe. For the completely open case the air feed line was inserted about six inches into the pipe, and no attempt was made to prevent back flow. Under these conditions no ignition could be obtained.

Test data obtained with the upstream end closed, with a mixture of 4 per cent propane in air and with the heater removed (no singing), are summarized in Table VIII. The averages of the five tests indicate peaks similar to those at zero wattage with the plenum (Table VII), except that the upstream peak is displaced from between thermocouples 3 and 4 to

TABLE VII

Average Values of Flame Propagation Rate at Various Distances from Ignition for a Mixture of 4 per cent Propane in Air Flowing in a 2-in. Pipe 56-in. Long With and Without Acoustical Resonance

Heater Wattage (watts)	Average Flame Propagation Rates Between Designated Thermocouple Positions (ft/sec)						No. of Tests	Maximum Flame Propagation Rates (ft/sec)
	Tc_{1-2}	Tc_{2-3}	Tc_{3-4}	Tc_{4-5}	Tc_{5-6}	Tc_{6-7}		
0	16.4	22.8	29.2	23.9	33.5	24.3	6	46.8
200	18.6	25.3	27.1	25.4	26.0	20.3	8	42.2
400	19.6	25.5	28.7	26.9	35.7	25.7	8	47.8
600	19.7	26.6	30.0	25.0	22.2	21.1	6	44.8

TABLE VIII

Average Values of Flame Propagation Rates from a Mixture of 4 per cent Propane in Air in a 2-in. Pipe 56-in. Long - Downstream End of Pipe Closed with Rubber Stopper (Each Value Averaged from 5 Tests)

Thermocouples	Ave. Propagation Rate (ft/sec)
1-2	22.8
2-3	28.6
3-4	21.5
4-5	34.5
5-6	42.4
6-7	33.7

Maximum Propagation Rate (Tc_{5-6}) = 62.3 ft/sec between thermocouples 2 and 3. On the basis of Laustsen's results(1) it was also expected that the flame propagation rates would be significantly higher for the closed-end case as compared to the open-ended (with feed plenum) case. Comparison of the values of Table VII with those of Table VIII indicate that the propagation rates of the closed-end case were on the order of 50 per cent higher than those obtained with the plenum. It is possible that the presence of the plenum resulted in our condition being effectively one of a partially-closed end, but the comparative results obtained may also have been influenced by the sound-absorbing properties of the rubber stopper. The data for the zero-wattage condition from Tables VII and VIII are plotted together on Figure 10.

2.3.5 Effect of Mixture Ratio

One series of tests was performed to ascertain the relative effects of the resonance produced at a heater wattage of 350 watts as a function of mixture ratio. A summary of the data from these tests is presented in Table IX. These data indicate that relatively higher peak values of flame propagation rate (ratio of peak value to value at zero wattage) could be obtained with the leaner mixture. However, there was little difference between the ratios of average values at 350 watts to average values at zero watts for the two mixture ratios.

2.3.6 Properties of the Acoustical Resonance

The acoustical resonance (singing) resulting at heater wattages above about 150 watts was subjected to some analysis as to the components of the waveform observed. The basic frequencies observed were 175 cps for the 36-in. pipe and 125 cps for the 56-in. pipe. These frequencies can also be regarded as the fundamental frequencies for the two respective lengths, although there is a slight deviation from the theoretical fundamental frequencies for these lengths. However, such deviation is to be expected due to the presence of equipment inside the tube, effects of the plenum, and non-ideal ends of the pipes.

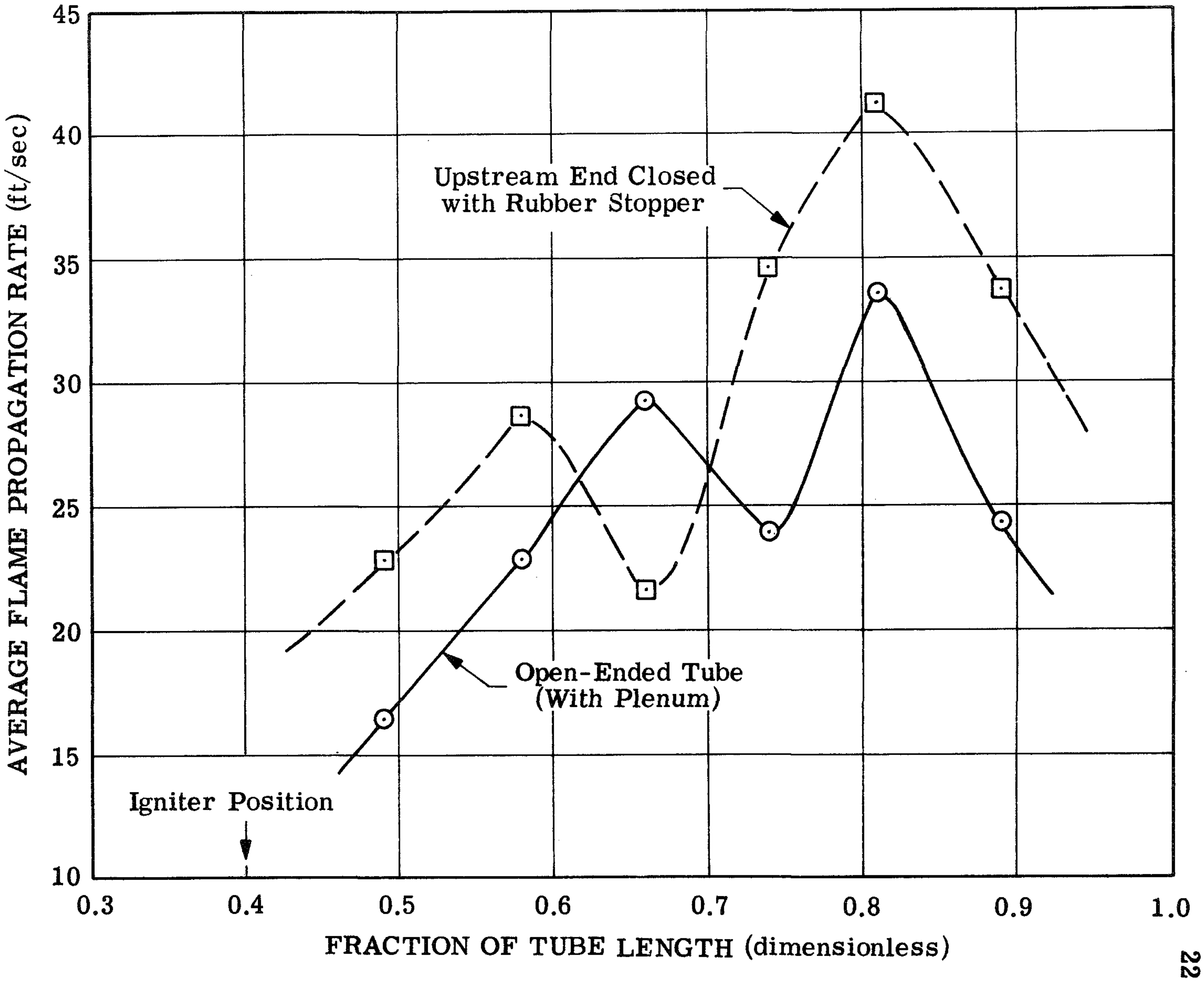


Figure 10. Effect of Closing Upstream End of 2-Inch Pipe (56-Inches Long) with a Rubber Stopper on Flame Propagation Rates along the Pipe. Mixture was 4 Percent Propane in Air.

TABLE IX

Effect of Mixture Ratio on Increases in Flame Propagation Rates due to Acoustical Resonance in a 2-in. Pipe 36-in. Long

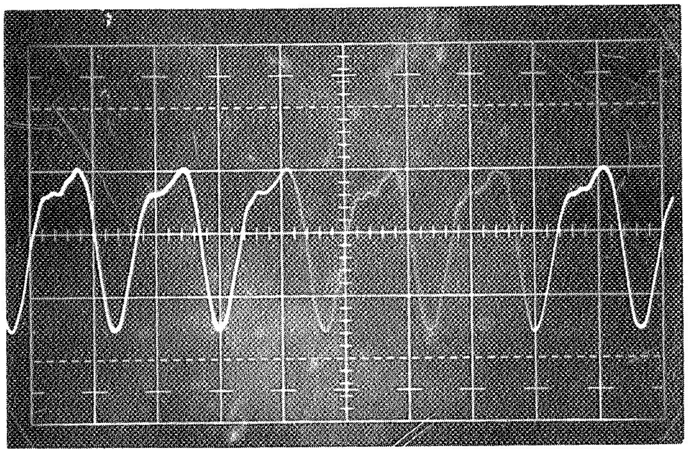
Mixture (per cent propane in air)	Heater Wattage (watts)	Flame Propagation Rates (ft/sec)			No. of Tests
		Minimum	Maximum	Average	
2	0	4.3	14.1	10.1	5
2	350	5.7	27.0	12.1	5
4	0	14.5	24.2	18.7	5
4	350	17.1	32.4	22.8	9

When no singing was present the passage of the flame front also generated acoustical signals of much lower db (sound pressure) levels than the singing, but the frequencies of the flame-generated signals were approximately the respective fundamental frequencies stated above. When singing was present the acoustic signal usually was reduced somewhat during passage of the flame front past the thermocouple positions. After the flame front had exited from the tube the db level of the singing diminished even further (or increased greatly in a few instances), even to the point of reduction by more than 20 db in some tests. A correlation was sought between the magnitude of the db change during flame propagation and the magnitude of the effect of resonance on flame propagation, but no such correlation could be established.

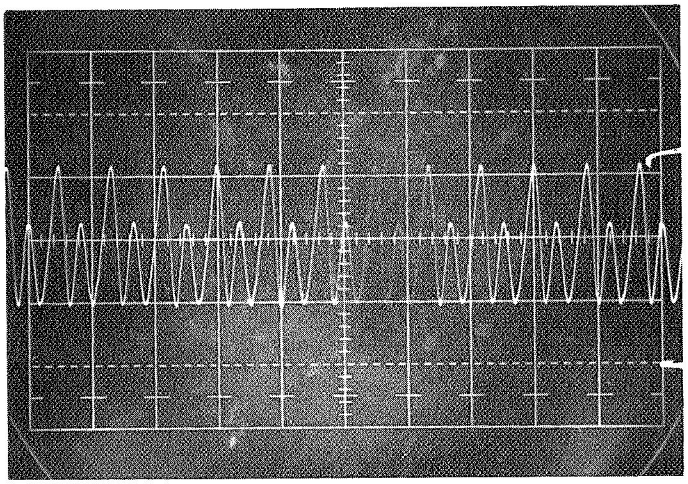
Observation of the shape of the acoustic signal as presented on the oscillographic traces and on an oscilloscope screen revealed that the fundamental frequency predominated throughout the tests with the shorter (36-in.) tube, even during the period of flame front passage through the tube. However, for the tests with the 56-in. tube, the first harmonic and the fundamental frequencies were usually of approximately equal magnitude during the singing. As the flame front passed through the longer tube the first harmonic was typically strengthened relative to the fundamental (total amplitude was decreased). In a few tests the second harmonic of the fundamental was evident from the oscillograph trace during flame front passage, but was of much lower amplitude than either the fundamental or the first harmonic.

Typical oscilloscope traces for the acoustic resonance (singing) present with both tube lengths are presented in Figure 11. For the long-tube case the first harmonic is very similar in amplitude to the fundamental, as determined by a graphical technique.

A possible correlation was sought between heater wattage and the



Singing in 36-Inch Pipe (Fundamental Frequency 175 Hz)



Singing in 56-Inch Pipe (Fundamental Frequency 125 Hz)

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Figure 11. Oscilloscope Traces of Acoustic Resonance (Singing) in Two Lengths of 2-Inch Pipe Without Flame Propagation.

relative magnitudes of the fundamental and first harmonic frequencies for the longer tube during flame front passage. Such a correlation could not be found. In addition, there did not appear to be a significant dependence of the maximum values (peaking) of flame propagation rates upon the nature of the acoustic signal at the tube exit.

3.0 DISCUSSION AND ANALYSIS OF RESULTS

Analysis of the results presented in Section 2.0, plus analysis of the results reported by Laustsen in Reference 1, have led to a generalized hypothesis for the basis of the effects of acoustical fields on flame propagation rates. This hypothesis is developed and discussed in the following sections, including a detailed interpretation of Laustsen's results in Section 3.5.

3.1 RELATION OF STANDING ACOUSTIC WAVES TO FLAME PROPAGATION RATE

A standing acoustic wave in a tube consists of a regular periodic array of particle velocities ranging from near zero at velocity nodes and maximum values at velocity loops. The acoustic field causes the particles (or molecules) to oscillate at frequencies dependent primarily upon the geometry of the tube. In a relatively short tube the major standing wave will correspond to the fundamental frequency of the tube, whereas in a relatively longer tube harmonics of the fundamental mode are to be expected.

Dynamic pressure in a tube in which a standing acoustic wave is established varies in a manner exactly out of phase with the particle velocity; a velocity node (minimum particle velocity) corresponds to a pressure loop (maximum dynamic-pressure variations) and a velocity loop corresponds to a pressure node. Laustsen(1) showed that the propagation-rate maxima in his plots of flame propagation rate versus distance from ignition source corresponds to minima (nodes) in the plot of dynamic pressure versus length.

Propagation rate data obtained with the longer (56-in.) tube in our work substantiate the relationship of velocity loops with peaks in the plot of propagation rate versus tube length (with no singing) in Figures 9 and 10. In this case the sound source which gives rise to the standing acoustic wave is the moving flame front. As shown on Figure 11, the fundamental and first partial mode (first harmonic) were both strongly present in the 56-in. tube when singing was occurring. The schematic particle velocity variations corresponding to the standing waves associated with these two acoustic modes for an open-ended tube are presented as (a) and (b) in Figure 12. The idealized bimodal combination of these standing waves would include interacting velocity loops between 0.5 L and 0.75 L, a partial velocity node at 0.75 L, and reinforced loop development between 0.75 L and L.

Assuming, then, that the propagation rate in the 56-in. tube followed the effective particle velocity, the following variation would be expected. Following ignition at 0.4 L, flame front velocity should accelerate through the loop formation and interaction, decelerate as a result of the partial node at 0.75 L, and accelerate again due to the strong loop formation beyond 0.75 L. According to Figure 9, this was the observed behavior in the absence of singing.

A deceleration near L (the downstream end) is also to be expected, since the high particle velocities ("pumping" effect) associated with the loop at that position will draw in fresh air from outside the tube, reduce the propane concentration, and thus reduce the propagation rate.

The proposed relationship between velocity loops and accelerated flame propagation rates is strengthened by analysis of the test results obtained with the upstream end of the 56-in. tube closed by a rubber stopper (Figure 10). The standing-wave patterns corresponding to the fundamental and first harmonics for the one-closed-end condition are shown schematically as (a) and (b) in Figure 13. With the upstream end closed, a combination of these two standing waves would result in a strong velocity loop between zero and 0.67 L, a partial node at 0.67 L, and a strong loop development between 0.67 L and L. Since the partial node here is moved upstream (at 0.67 L) compared to 0.75 L for the open-end case, it would be expected that the minimum in the flame propagation rate versus distance plot would be moved somewhat upstream by the effect of the closed end, and that the same upstream displacement would be true of the first (upstream) propagation-rate peak. According to Figure 10 this was the observed behavior. After ignition at 0.4 L the first peak

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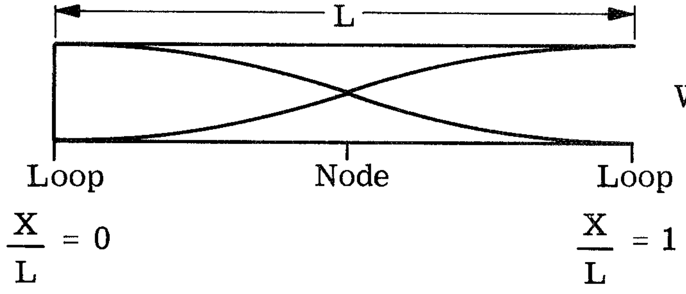
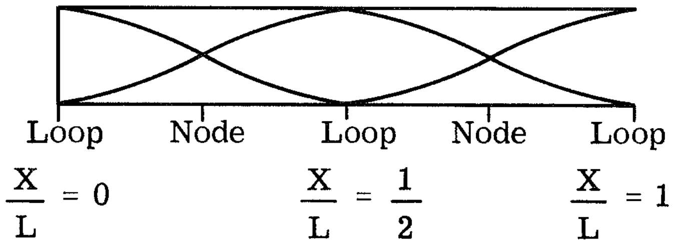


$$L = \frac{\lambda_f}{2}$$

Where λ_f = Wave Length of Fundamental Tone

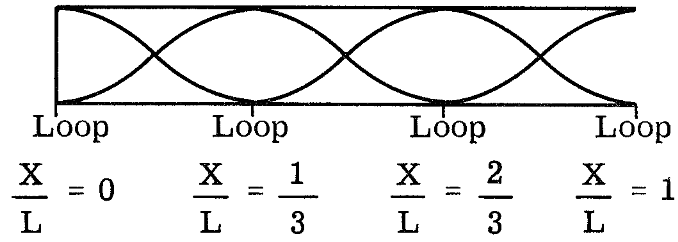
a. Fundamental



$$\lambda_1 = \frac{\lambda_f}{2}$$

$$L = \lambda_1$$

b. First Partial Mode (First Harmonic)

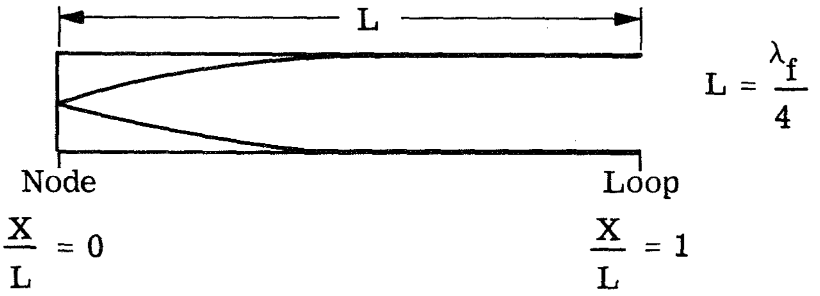


$$\lambda_2 = \frac{\lambda_f}{3}$$

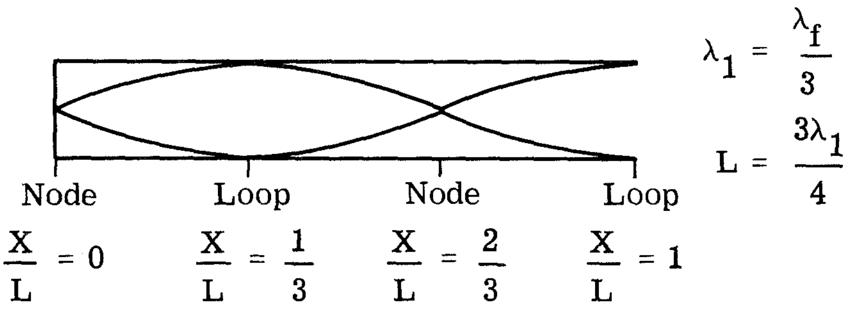
$$L = \frac{3\lambda_2}{2}$$

c. Second Partial Mode (Second Harmonic)

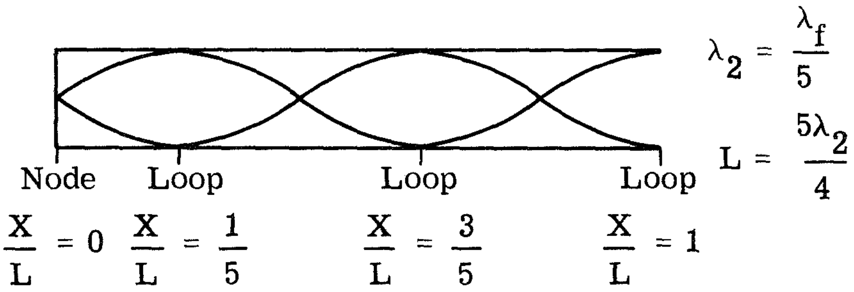
Figure 12. Idealized Standing Waves on an Open-Ended Tube (Particle Velocity Variation with Length).



a. Fundamental



b. First Partial Mode (First Harmonic)



c. Second Partial Mode (Second Harmonic)

Figure 13. Idealized Standing Waves in a Tube with the Upstream End Closed (Particle Velocity Variation with Length).

occurred around 0.55 L (compared to 0.65 L for the open-end case), the minimum occurred at about 0.65 L (compared with approximately 0.75 L for the open-end case), and the second peak occurred again at about 0.8 L.

3.2 MECHANISMS OF PROPAGATION ENHANCEMENT BY VELOCITY LOOPS

Acceleration of flame velocity is generally associated with a progressive wrinkling of the flame front, so that the major contribution to the increase in combustion rate is the increase in flame front area. For a flame front in a tube under low or zero flow conditions, a steady-state condition of a smooth ("spoon-shaped") flame front is maintained because most of the shear stress experienced by the gas is near the tube wall and the tube wall is a quenching surface which can capture chain-carrying radicals. Any process which causes increased shear (or mixing) to be present throughout the tube, instead of mostly near the wall, will result in wrinkling of the flame front and enhancement of flame velocity.

This point was well illustrated by the work of Evans, Scheer, Schoen, and Miller(8), who studied the significant enhancement of flame velocity in tubes resulting from passage of the flame front through a grid. The flame front downstream of the grid was cellular and wrinkled, and the flame velocity was increased as much as a factor of ten compared to the velocities upstream of the grid. The presence of the grid provided strong local shearing over the entire cross section of the tube, as a result of flame-front jetting through the holes in the grid.

In a velocity loop associated with a standing acoustical wave, increased local shearing is provided by the particle (molecular) oscillations at the various frequencies present. It is this provision of shearing (or mixing, or "turbulence") in the center of the tube which we believe is responsible for increases of flame velocity at velocity loops. It was shown by Meyer and Güth(9) that the particle velocity at a loop is greater at the center of the tube than at the wall. Thus, the shearing due to the velocity loop is strongest away from the wall, whereas the shearing due to flow velocity is strongest near the wall. It is this difference which accounts for the relatively weak dependence of flame velocity in gases on Reynolds number as compared to the strong dependence upon loop formation (apparently) observed in this study.

Several other points concerning Reference 8 should be discussed. From examination of Figures 2, 4 and 5 of Reference 8, it is apparent that the two propagation-rate peaks along the length of the 4-in.-diameter tubes were observed by Evans, et al, both with and without the grid. When the grid was present the two peaks referred to occurred downstream of the grid. However, the authors' interpretation of this peaking was that it was due to first reflections of pressure waves from the grid and from the open downstream end. This interpretation may be questioned because the reflection from an open end will be a rarefaction wave and not a compression wave. Such a wave produces a less dense medium in its wake, which suggests a decrease of flame velocity rather than an acceleration, if any direct effect were produced. However, standing-wave patterns, which are a secondary effect of such reflections, appear to be a more probable cause of the observed peaking. The observation on which the interpretation of Evans and her co-workers was based indicated that the peaking occurred later for longer tubes. This behavior would be better explained if it were assumed (as in the case of our analysis) that standing-wave velocity loops caused the peaking, so long as the flame velocity versus downstream distance from the grid was reasonably similar over the first half of the tube length (which was the case, according to the data in Reference 8).

3.3 INTERPRETATION OF ACOUSTICAL RESONANCE (SINGING) EFFECTS

All of the discussion thus far in this section has not involved effects of the acoustic resonance, or singing. In the succeeding paragraphs we will attempt to interpret the results with singing, based on the demonstrated relationship between propagation-rate peaks and velocity loops present in acoustical standing waves.

In Section 2.1.3 it was hypothesized that vortices, or recirculatory flow cells, form during singing. However, since no evidence was obtained to indicate that these cells would ever extend far enough (radially) into the stream to add significant shearing into the flame front, and since no cell geometry can be hypothesized which would fit the data obtained even if the cells did extend well into the flow stream, it is assumed that cell effects on propagation rates in this program were insignificant.

It is proposed that the observed effects of the singing were due to standing acoustic waves, of as yet undefined characteristics, resulting from the resonance. It is well known that standing waves can occur in a number of modes in a strong acoustic field, and also that the location of nodes and loops can shift and vary greatly in position even in an apparent steady-state condition. Based on the apparent strong effects of velocity loops on flame propagation rate discussed previously, it is suggested that the strong peaking in flame velocities observed with singing were caused by a coupling, or reinforcement, of the velocity loops arising from the flame front with a strong velocity loop associated with the standing wave arising from the singing, under certain conditions. The data seems to indicate that there was only one such interaction of velocity loops in the 36-in. tube, occurring at approximately 2L/3. Strong coupling also occurred at approximately 0.8 L for the 56-in. tube at heater wattages of 350 to 450 watts, and a velocity loop probably due only to the singing is believed to have been present at about 2L/3 at 600 watts.

One expected result of a complex standing wave arising from the singing would be a general interference (cancellation) of the velocity loops (and, thus, propagation-rate peaking) produced by the simpler standing wave from the flame front, except where coupling occurred. This behavior was observed in the 56-in. tube, as shown in Table VII. The observed reduction of propagation rates (to values below the initial rate) both upstream and downstream of the strong peaking at 350 watts with the 36-in. tube (Table I) is very difficult to explain. Perhaps this behavior was associated with enhanced heat transfer to the tube wall, which is often an effect of an acoustical field on a heat transfer process(4,5). However, a more likely explanation is that the strong velocity loop in the coupled condition terminates on both sides into standing vortices which tend to direct the flow into the tube wall, causing cooling and quenching effects.

3.4 PREDICTION OF PROPAGATION "CASCADING" IN LONG TUBES

One salient feature of all results referred to or reported herein for the downstream tube end open is that for sufficiently long tubes two peaks in propagation rate are found, and the second peak always represents a higher maximum value of propagation rate than the first. It seems quite possible that extension of the tube length so that more and more velocity loops are available (due to the attendant inclusion of higher harmonics) to accelerate the flame front might result in a number of peaks of continually increasing propagation rate. If this were the case, then it would be easy to visualize a situation in which propagation of flame through a very long tube (such as an aircraft vent line) might result in a detonation either in the tube or in semi-enclosed tankage filled with flammable mixture located at the end of the tube. This type of "cascading" might well be the mechanism by which the "cascading" proposed by von Elbe(10) in vent systems could occur. It is recommended that the above phenomenon, that is, a number of successive increases of flame propagation rate in a long tube, be sought and characterized in a future effort. Such an effect could be an insidious source of safety hazards in aircraft fuel system designs, or configurations for other types of aerospace systems.

3.5 INTERPRETATION OF LAUSTSEN'S DATA

In the preceding subsections of Section 3.0, an analysis of the results of our flame propagation experiments with and without induced "singing" effects, has been presented. This analysis is based strongly upon the hypothesis that velocity loops and nodes, associated with acoustical standing waves which have been produced in the duct by the flame front, are responsible for acceleration and deceleration of the flame front as it travels the tube length. These effects appear as pronounced peaks and valleys in graphical representations of local flame-propagation rates versus distance along the tube length from the ignition source. Similarly, the effects on flame propagation rates of induced "singing" in the tube seem to involve a coupling between the standing wave(s) produced by the flame front and the standing wave(s) produced by the acoustic driver (heater element). Because this hypothesized mechanism correlates the results of our experiments very effectively, it was of interest to also determine its effectiveness in plausibly interpreting the results obtained by other investigators. The paper by Laustsen(1), which was commented upon earlier in this report, was found to be the best source of appropriate data with which to test the general effectiveness of our analytical approach. Results of the application of our analysis for the interpretation of Laustsen's data are presented in the following subsections.

3.5.1 Open Tube with Ignition-End Orifices

One group of Laustsen's experiments involved flame-propagation rate measurements in a tube configuration having both ends completely open, initially; then for successive tests the ignition end (only) was provided with an orifice place in which the orifice was made smaller from test to test until that end was completely closed. From a general review of the graphical representation of these data, it appears that progressive decreases (constrictions) in the diameter (without closing it entirely) intensify the heights of peaks in the flame-speed versus time plots and shift the X/L location of the upstream peak slightly toward the ignition end. If one portrays the initial acoustical mode in the tube, created by the flame-front disturbance, as the fundamental mode for an open-ended organ pipe, the schematic representation for the attendant standing wave is the same as that shown before in Figure 12a. As has been discussed in Section 3.1, the "loops" are velocity antinodes and are therefore characterized by maximum amplitudes for vibrations of particles which constitute the gaseous medium inside the tube. Similarly, the node is a point of no vibrations of particles; at least none attributable directly to acoustical effects which produced the standing wave. Therefore, for the case represented by Figure 12a, particles would be expected to vibrate with maximum amplitude at X/L = 0, with the amplitudes decreasing in the direction of increasing X/L to X/L = 0.5, then increasing again between X/L = 0.5 and X/L = 1, to approach maximum amplitude again at X/L = 1.

Based upon this physical process associated with standing-wave phenomena in gas-filled, open tubes, several effects can be postulated. Assuming that ignition in the tube, with both ends completely open, sets up this predominantly fundamental mode in the tube, the regions of higher gas-particle velocities (oscillatory) at the ignition-end antinode can cause acceleration of flame propagation shortly after ignition (probably due to intensified shear-stress effects in the region of antinode influence). Further downstream, the superimposed effects of the ignition-end antinode dissipate and the flame-front decelerates to approach standard flame-velocity levels as it overtakes and mixes with undisturbed gas in the region of the velocity node at $X/L \sim 0.5$. Then, downstream from this node, the effects of the exit-end antinode once again tend to accelerate the flame front, and this continues up to some critical region very near the exit end of the tube. Here, the rapid particle oscillations tend to pull in air from the external environment of the tube, diluting the fuel-air mixture until combustion cannot be sustained as effectively and the flame-propagation velocity sharply decreases. This trend is shown weakly by the lowest curve in Figure 14, which is our reproduction of Figure II in Laustsen's report(1).

Then, as the upstream (ignition) end of the tube is progressively constricted by orifices of various diameters, the velocities of particle oscillations produced by the antinode at that end can be expected to become higher and higher. Those higher velocities that are induced by moderate flow constrictions in turn can be expected to somewhat intensify and exaggerate the peaking effect just downstream from the ignition point. In addition, the intensified upstream effect probably can stimulate a significantly exaggerated peaking effect downstream in the region of particle acceleration produced by the exit-end antinode. The latter effect would be attributable to the higher velocity of the flame front as it enters that region, even

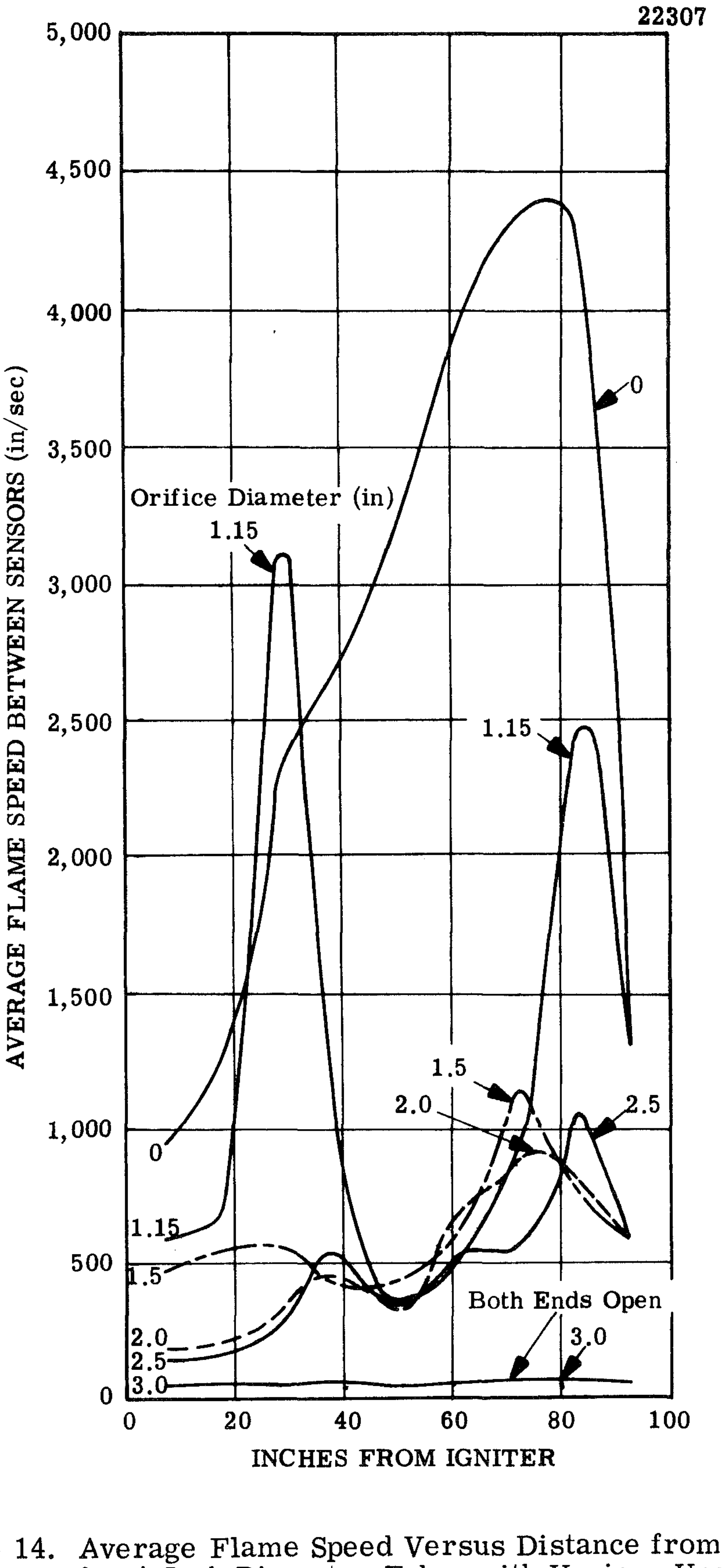


Figure 14. Average Flame Speed Versus Distance from Igniter for 4-Inch Diameter Tubes with Various Upstream End Orifice Diameter (Figure II of Reference 1).

though some deceleration of the flame-front would be expected in the region of the velocity node near X/L = 0.5. Of course, the end-effect dilution of the fuel-air mixture would again sharply decrease flame propagation in the immediate vicinity of X/L = 1. This trend is shown very strongly by Laustsen's curves for orifice diameters of 2.5, 2.0, and 1.5 inches in Figure 14.

A close study of Laustsen's data curve for an ignition-end orifice diameter of 1.15 inches in Figure 14 suggests the onset of a "threshold" effect; i.e., a transition to a much greater intensification of the peaking of flame propagation rate for orifice diameters that are smaller than some "minimum". Above this minimum, the effects described above, for the larger orifices, predominate. One possible acoustical explanation for such a threshold effect would be the onset of a more complicated standing-wave pattern in the tube for entrance-end orifices smaller than the "minimum". For example, it can be reasoned that these sub-minimum orifice diameters do not permit their end of the tube to behave like a true "open end" of an organ pipe, but instead cause it to serve both as an open-end and a closed-end acoustical reflection site. Thus, only part of the energy is permitted to escape that end because of the limitations imposed by the relatively small orifice, and the remainder is reflected back up the tube (toward X/L = 1) as a compression wave (closed-end effect). Nevertheless, the energy that does escape through the orifice creates an open-end effect similar to that described above for the larger orifices, but producing even greater velocities of particle oscillations because of the small flow area. Although our experimental results to date do not permit us to specify or characterize exactly the complex standing-wave pattern produced in the tube for this case, Laustsen's data strongly suggest a coupling between the fundamental mode for open-tube phenomena and the first partial mode for semi-closed-end phenomena. The latter mode, by itself, can be represented schematically as shown in Figure 13b.

This combination of acoustical effects would tend to:

(1) further increase the initial flame-propagation velocity at the ignition point (as compared with values for the larger orifices, above the "minimum" diameter);

(2) greatly increase the particle velocities in the gaseous medium ahead of the flame front in the region of strong interaction between the two standing-wave effects, near X/L = 0.2 (a developing loop from the reflected compression wave and a decaying loop from the reflected rarefaction wave both have vigorous particle oscillations), greatly intensifying the acceleration of flame propagation in the region just downstream from this location;

(3) sharply decrease particle velocities and suppress flame-propagation velocity in regions of influence of the two nodes (located at X/L = 0.5 and X/L = 0.67, respectively); then

(4) sharply accelerate particle oscillations and the flame front again, in the region downstream from the node at X/L = 0.67, under the influence of the two developing loops that would start interacting strongly at that point; until

(5) the end-effect pumping and dilution near X/L = 1.0 would again sharply decrease flame propagation over the remainder of the tube length. This hypothesized interaction of acoustical nodes and their resultant effects on flame propagation in such a tube configuration are consistent with the data presented by Laustsen (in his Figure II) for the ignition-end orifice diameter of 1.15 inches.

3.5.2 Other Tube-End Configurations

The final data curve on Figure 14 represents Laustsen's results using a tube that was completely closed at the ignition end and completely open at the opposite end. Applying our hypothesized mechanism to this case, it can be seen from the figure that any acoustical standing-wave effects must have been capable of producing continuous and intensified accelerations of the flame front along the entire length of the tube (except, of course for the usual sharp deceleration at the open exit end). We have interpreted this effect to be a result of standing-wave patterns produced by either the fundamental acoustical mode for this pipe configuration (see Figure 13a), or the first partial mode (Figure 13b), or a complex combination of these two modes. Any one of these loop-node patterns offers a plausible explanation of the observed flame-propagation behavior, and the present lack of better information prevents exact characterization of the pattern which actually controls this behavior. But it can be seen that either of the candidate patterns shows a very energetic compression-wave reflection from the closed end, with minimum loss of energy from the tube at that site. This effect leads into the development of a single strong loop for the fundamental mode, two loops for the first partial mode, or a combination of effects for a bimodal pattern. If either of the latter two patterns predominates, the associated node near X/L = 2/3 must obviously have little effect on the flame propagation mechanism. This seems reasonable for both cases because the very strong ignition-end reflection would be expected not only to produce stronger loop effects, but also to propagate through the flame front, in the direction of flame propagation, with greater strength (and probably greater shearing effects) than would be expected for a tube with a completely or partially open ignition-end. Thus, it follows that the additionally vigorous acceleration imparted to the flame front in the region of the first loop, together with the boosting effect of the closed-end reflection, could at least partially sustain the acceleration through a relatively short nodal region.

Application of our analytical technique and mechanism hypothesis to the remaining data reported by Laustsen in Reference 1, and reproduced by us on Figure 15, results in equally plausible and consistent physical interpretations of the flame-propagation trends. Certainly, this adds greatly to our confidence in the technique and the hypothesis, and therefore

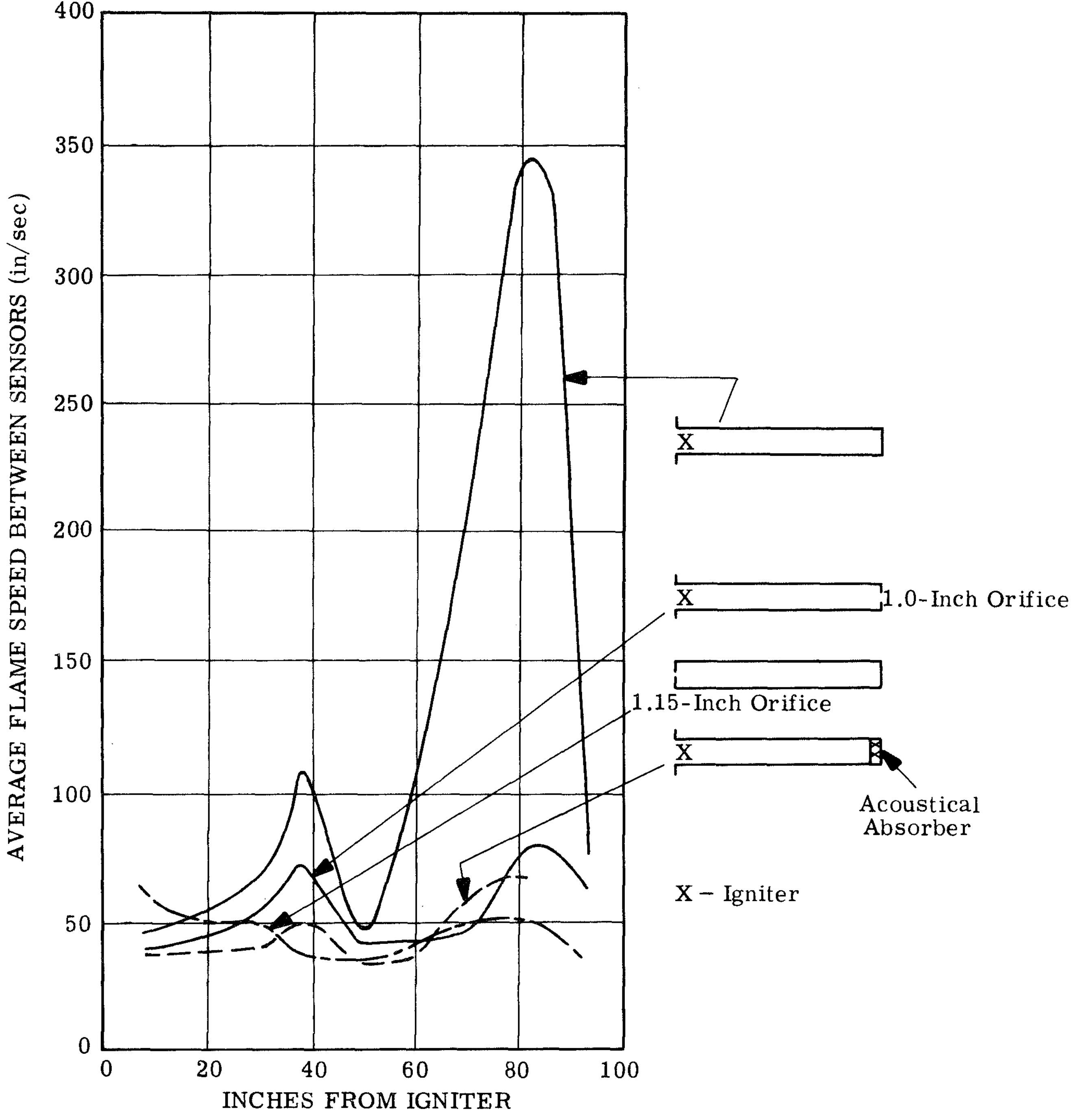


Figure 15. Average Flame Speed Versus Distance from Igniter for 4-Inch Diameter Tube with Various Configurations (Figure III of Reference 1).

to our interpretation of our own experimental results. But final satisfaction with this analysis awaits further experimental verification (and perhaps a correlating mathematical model) of the acoustical modes which are produced in various types of tube geometries under the conditions described in this report, and the associated mechanisms which apparently couple acoustical, combustion and transport phenomena in such systems.

4.0 CONCLUSIONS

The following conclusions result from the data and analysis presented in preceding sections of this report:

(1) Significant increases (peaking) in flame velocity for hydrocarbon-air mixtures occur in open-ended tubes having certain geometrical configurations in the absence of externally-produced acoustical fields.

(2) These increases (peaks) in flame velocity can be strongly augmented by the presence of an externally-produced resonant acoustic field ("singing") in the tube.

(3) The locations of the flame velocity peaks along the tube length correspond to predicted locations of velocity loops associated with standing-wave patterns arising from the acoustical field present in the tube.

(4) When the resonant acoustical field arises from the flame front alone, the positions of the flame velocity peaks are dependent upon the length (and probably the diameter) of the tube.

(5) When two acoustical sources, each of sufficient strength, exist in the tube (e.g., one combustion-derived and the other externally induced), local flame velocity increases of a factor of two or three above normal flame velocities result from strong reinforcement of velocity loops; similarly, cancellation effects occur at other locations along the tube length.

(6) Experimental results indicate that such strong velocity-loop reinforcement does not always occur when conditions are kept similar.

(7) The analytical basis used for the correlation of the data form from this program involves the assessment of velocity-loop effects, produced by "organ pipe" behavior, on flame propagation. This method can be used to predict and interpret flame-front

behavior in tube systems of various configurations.

(8) The mechanism by which velocity loops produce flame-front acceleration involves an increase of shearing effects over the entire cross-section of a duct.

(9) Extrapolation of the data obtained from this program to the case of much longer tubesindicates a significant probability that complex velocity-loop patterns could give rise to a number of successively higher flame velocity peaks ("cascading" of flame velocity). Such an occurrence could constitute a detonation hazard in certain aircraft fuel system designs.

5.0 RECOMMENDATIONS

The following recommendations for future work are based on the results and conclusions from this program:

(1) It is recommended that the contribution of velocity loops (present in standing acoustic waves) toward flame front acceleration in ducts be further established and clarified.

(2) It is recommended that flame velocity peaking due to reinforcement effects between two sound sources in a duct (one arising from the flame front and the other externally impressed) be investigated with regard to the attainment of detonation velocities.

(3) It is recommended that the predicted "cascading" of successively higher flame velocity peaks (caused by the acoustic field arising from the flame front alone) in very long ducts be investigated.

(4) It is recommended that potential hazards, particularly hazards to certain aircraft fuel tankage vent systems, associated with acoustically-induced flame velocity increases be evaluated.

6.0 REFERENCES

1.0 Laustsen, R., "Investigations of Flame Propagation in Tubes and 'Safom' as a Flame Arrestor", Paper No. WSCI-68-12, Presented to the Western States Section of the Combustion Institute, Los Angeles, Calif. (April, 1968).

2\. Spurlock, J.M., "The Effects of Acoustic Vibrations on Air in a Resonant Horizontal Tube with and Without Throughflow", Ph.D. Thesis, Dept. of Chem. Engr., Georgia Inst. Tech. (1961).

3\. Purdy, K.R., "Viscous Fluid Flow under the Influence of a Resonant Acoustic Field," Ph.D. Thesis, Dept. of Chem. Engr., Georgia Inst. Tech. (1963).

4\. Spurlock, J.M., T.W. Jackson, K.R. Purdy, C.C. Oliver, and H.L. Johnson, "The Effects of Resonant Acoustic Vibrations on Heat Transfer to Air in Horizontal Tubes", WADC Technical Note 59-330, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio (1959).

5\. Jackson, T.W., K.R. Purdy, C.C. Oliver, and H.L. Johnson, "The Effects of Resonant Acoustic Vibrations on the Local and Overall Heat Transfer Coefficients for Air Flowing Through an Isothermal Horizontal Tube", ARL Technical Report 60-322, Aeronautical Research Laboratory, Wright-Patterson Air Force Base, Ohio (1960).

6\. Lord Rayleigh, "The Theory of Sound", Vol. II (First Published 1878), pp 227-230 Dover Edition (1945).

7\. Putnam, A.A., "General Considerations of Autonomous Combustion Oscillations", Battelle Memorial Institute Report (1959). See also Putnam, A.A., and W.R. Dennis, J. Acous. Soc. Am., 28, pp 246-249 (1956).

8\. Evans, M.W., M.D. Scheer, L.J. Schoen, and E.L. Miller, "A Study of High Velocity Flames Developed by Grids in Tubes". Proceedings of the Third Symposium on Combustion, Flame and Explosion Phenomena, pp 168-176. Williams and Wilkins Co., Baltimore, Md., (1949).

9\. Meyer, E., and W. Güth, "Zur Akustischen Zähigkeitsgrenzschicht", Acustica, 3, pp. 185-7 (1953).

10\. Bolta, C.C., R. Friedman, G.M. Griner, M. Markels, Jr., M.W. Tobriner, and G. von Elbe, "Lightning Protection Measures for Aircraft Fuel Systems", FAA Technical Report ADS-18 (Phase II). Prepared by Atlantic Research Corporation, Alexandria, Va. for the Federal Aviation Agency, Washington, D.C. (May, 1964).

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