RP553

# THE EFFECT OF ALTITUDE ON THE LIMITS OF SAFE OPERATION OF GAS APPLIANCES[1]

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## ABSTRACT

The effects of altitude have been determined, from sea level to 11,000 feet, on the limits of safe operation of nine different gas appliances operated with a mixed city gas and in one case with propane.

It was found that the maximum safe gas rate, in B.t.u. per hour, is reduced by 3 to 4 per cent of the safe rate at sea level for each thousand feet of elevation. This reduction is about the same for all of the appliances tested with the exception of the radiant heaters which are more affected than the other types.

Data are presented from which preliminary estimates may be made of the size of the flue passages necessary at various altitudes for certain types of appliances. Other data show the effects of changes of altitude on the injection of primary air, the efficiency of the top burner of a range, the lifting of the flames from the ports, and the operation of pilot flames of both the "blue-flame" and "yellow-flame" types.

The effect of altitude in reducing the amount of gas that can be burned completely in a calorimeter was found to be the same with propane as with mixed city gas. It is concluded that the effects would have been the same had the comparison been made with other appliances or other gases.

Curves are presented which summarize the results quantitatively.

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## I. INTRODUCTION

During the several years since the establishment of the Cleveland Testing Laboratory by the American Gas Association, there has been continual cooperation between the association and the Bureau of Standards in the matter of fundamental investigations. The results obtained in such investigations have been used to formulate standard methods for testing gas appliances, and minimum requirements which

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[1] Presented in substance at the Washington meeting of the American Chemical Society, March 1933.
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various appliances should meet to insure safety and satisfactory service to the purchaser.

Largely as a matter of chance, the fundamental research which was necessary in order to draft approval requirements and also the routine testing of appliances to determine compliance with these requirements have been carried out at places which are not far above sea level.

The development of better methods of testing and the realization of the importance to the public of testing appliances have led to the establishment of various independent testing laboratories. Recently, one such laboratory, that of the Public Service Co. of Colorado in Denver, found that some of the appliances could not be operated with safety in Denver, at the gas rates for which they had been approved by the association's testing laboratory in Cleveland.

After a thorough checking of the results of both laboratories, the only reasonable explanation for such a failure of the standard test methods seemed to be the difference in the altitude of the two laboratories. Accordingly, the Bureau of Standards was asked to determine whether a change in altitude could account for the difficulties which had been encountered and to make a quantitative study of the effects on the limits of safe operation produced by changes of altitude. The Bureau was fortunate in having available an "altitude chamber" designed for the testing of aircraft motors which, with a few changes, was suitable for making appliance tests under substantially normal operating conditions at the barometric pressures corresponding to any desired altitude.

In order to make the results of this study generally applicable, and also to determine whether one type of appliance was more seriously affected than another, it was decided to test at least one representative approved model of each of the types of domestic gas appliances in most common use; namely, a water heater, a "circulating" space heater, a radiant heater, a range, and a central house-heating furnace. In all, eight appliances were tested with the mixed gas distributed in Washington. To these was added a manually operated gas calorimeter. The calorimeter was tested on the mixed gas and also with propane in order to determine whether the type of gas used affected the results.

## II. EQUIPMENT

Figure 1 shows the interior of the altitude chamber, with a gas range installed for test. The chamber, which was approximately 8 by 8 by 18 feet, was supplied with compressed air, gas, water, vacuum, and electric connections. A large rotary exhauster provided means for reducing the pressure in the chamber, which, with the use of valves, could be held constant to 2 mm of mercury or less, this corresponding to less than 100 feet of altitude.

The instruments shown in figure 1 [3] were used to determine: (*a*) gas rate, (*b*) gas pressure at the appliance, (*c*) the constancy of composition of the gas supply, (*d*) the proportion of primary air in the mixture being burned, (*e*) the proportion of carbon dioxide in the flue gases, (*f*) the temperature of the flue gases, (*g*) the percentage of

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[3] A Method for Determining the Most Favorable Design of Gas Burners, B.S.Jour. Research, vol. 8, p. 669 (RP446), 1932. Appendix describes the instruments for the determination of the data of items *c*, *d*, and *e*.

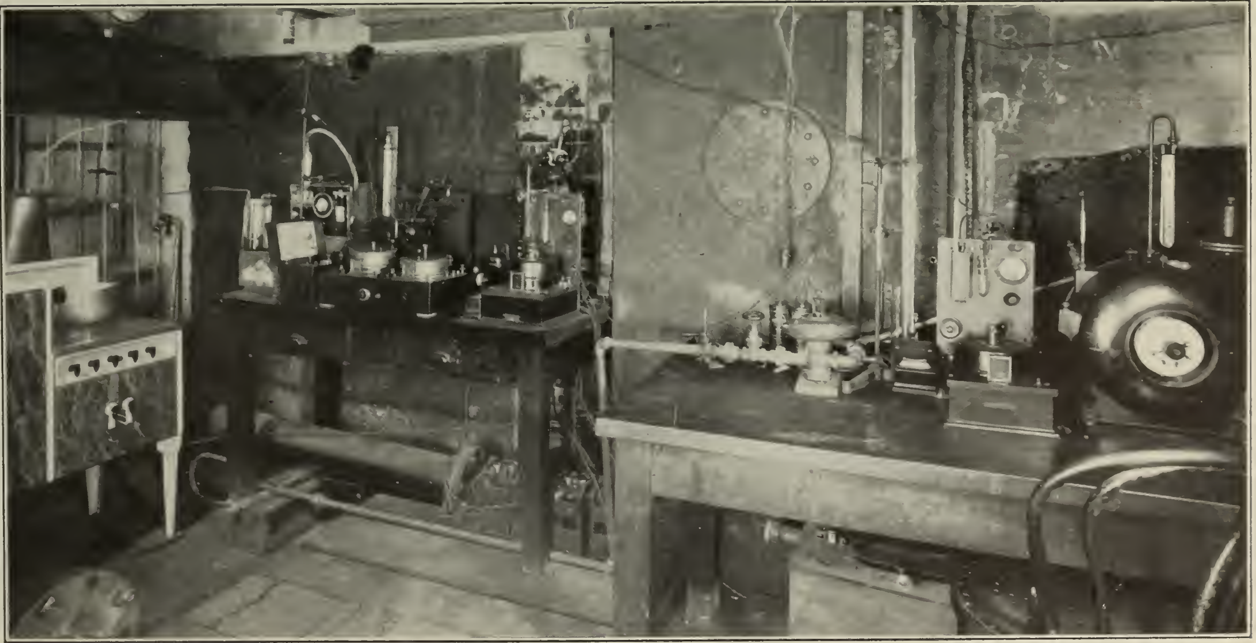

Figure 1.—*Interior of altitude chamber.*

carbon monoxide in the flue gases[4], (*h*) the temperature of the room, and (*i*) the barometric pressure, which throughout the paper will be expressed in terms of the altitude to which it corresponds.

In addition, provision was made for varying the area of the flue and for determining the efficiency of utilization of the heat from a top burner. A recording calorimeter located outside of the chamber made a continuous record of the heating value of the gas supply.

## III. APPLIANCES TESTED

The following appliances were tested: Two "side-arm" water heaters—one of the copper-coil type *A* and the other having a cast-iron water jacket *B;* one gas range with a solid top *C;* one single-burner hot plate *D* supplied with an open grid; three space heaters—one of the circulator type *E* and two of the radiant type *F* and *G;* one gas-fired warm-air furnace *H;* and one manually operated calorimeter *I.* All of these appliances (with the exception of the calorimeter) had been tested and approved by the testing laboratory of the American Gas Association.

The variations in design, character, and size of these appliances were considered to be sufficiently great to make the results of the study of this group accurately indicative of what might be expected from any applianace in common use at this time.

## IV. EFFECT OF ALTITUDE ON THE MAXIMUM SAFE GAS RATE

The method used for testing each of the appliances listed above was as follows: With the appliance installed in the altitude chamber in the usual manner and with the door of the chamber open (approximately sea level), the gas rate was adjusted to give the manufacturer's normal input rating measured in B.t.u. per hour. While the gas rate was held constant, the proportion of primary air to gas was varied from that which caused yellow-tipped flames to that which produced blowing or lifting of the flames. This variation was made in steps and the porportion of carbon monoxide and carbon dioxide in the flue gases determined at each step. The flue temperature and the relative proportions of primary air and gas were also recorded at each setting. By repeating this same procedure at several gas rates and plotting the primary air used against the carbon monoxide produced, it was possible to determine the amount of primary air which was required at each gas rate to give complete combustion.[5]

Backfiring was not a source of trouble with any of the appliances tested. There is every reason to believe that backfiring will occur less readily at a high than at a low elevation, hence this hazard was not studied.

The temperature of the flue gases was found to have very little relation to the altitude. It appeared to be almost entirely a function of the gas rate in B.t.u. per hour.

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[4] The instrument for the determination of carbon monoxide was a continuous indicator recently developed by the Mine Safety Appliances Co. for the Navy Department.

[5] The range of gas rates was determined by the amount of primary air required for complete combustion. The lowest gas rate was the one which produced no carbon monoxide until the primary air was reduced to an amount which caused yellow tips, while the highest gas rate was the one which did not permit complete combustion when the primary air was increased to an amount just less than that which caused lifting of the flames. For a complete discussion of this method of testing and of representing the results, see Research Paper No. 446, referred to in footnote 3, p. 620.

Similar curves were obtained in the same manner at other altitudes by closing the door of the chamber and exhausting the air until the pressure in the room was the same as the normal barometric pressure at the desired altitude.

Figure 2 shows the effect of altitude on the operation of water heater *B*, the appliance which was studied in the most detail. The maximum gas rate that can be safely used is shown by the intersection of the "0 percent CO curve" with the blowing curve obtained at the desired altitude. For example, at an altitude of 200 feet, this intersection occurs at a gas rate of 26,600 B.t.u. per hour while, at an altitude of 10,900 feet, the intersection of the corresponding carbon monoxide and blowing curves occurs at 17,200 B.t.u. per hour.

The facilities available in the altitude chamber did not permit the lifting of the flames of some of the appliances to be readily observed at their maximum safe gas rates. For this reason, as well as others, it seemed desirable to select, for comparisons between appliances, some basis other than the maximum safe rate. In the case of water heater *B*, it may be seen that the amount of air in the primary mixture which will permit gas to be burned safely at the maximum rate varies but little with altitude, from 61 percent of the total required at 200 feet to 57 percent at 10,900 feet. Most of the other appliances tested showed even narrower ranges of variation in the composition of the primary mixture which permits the use of a maximum amount of gas, and none of the five for which the necessary data were obtained showed a greater range. The range of uncertainty in the usual adjustment (by appearance) of appliances in use is considerably greater than this, hence no difference in the composition of the primary mixture supplied to appliances at various altitudes need be provided for by the designer or in the instructions to adjusters. There is no appreciable difference at different altitudes in the size or appearance of a flame produced by the same primary mixture burned

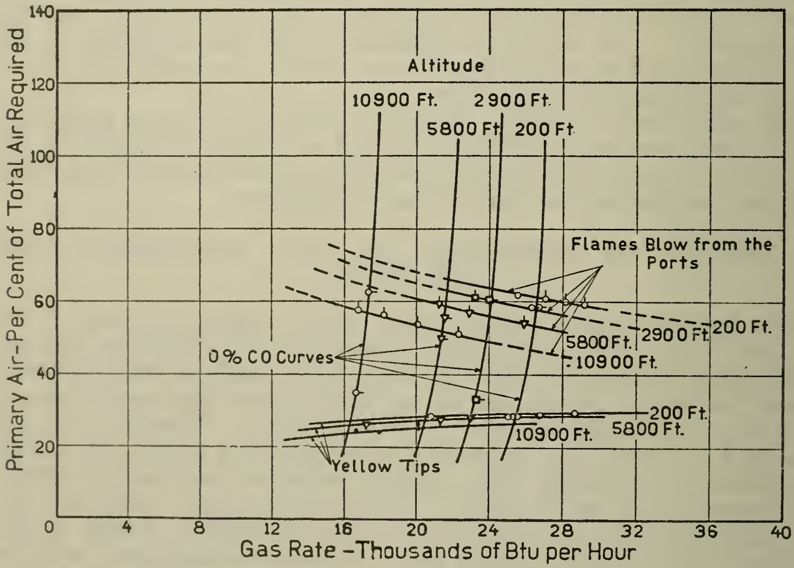

FIGURE 2.—*Effect of altitude on the limits of safe operation of water heater B.*

at the same rate in B.t.u. per hour. Differences of altitude may therefore be expected to have little or no effect on the average adjustment of appliances, with respect to either the gas rate or the composition of the primary mixture, if the appliances have been adjusted by appearance.

In view of these facts, it seems not only convenient but permissible to compare the operation of the same appliance at different altitudes when supplied with a primary mixture of the same composition, and similarly to base comparisons between different appliances on the same primary mixture. The mixture chosen for the purpose is one containing 55 percent of the "total air required"[6] for complete combustion and is probably near the average for which appliances are generally adjusted.

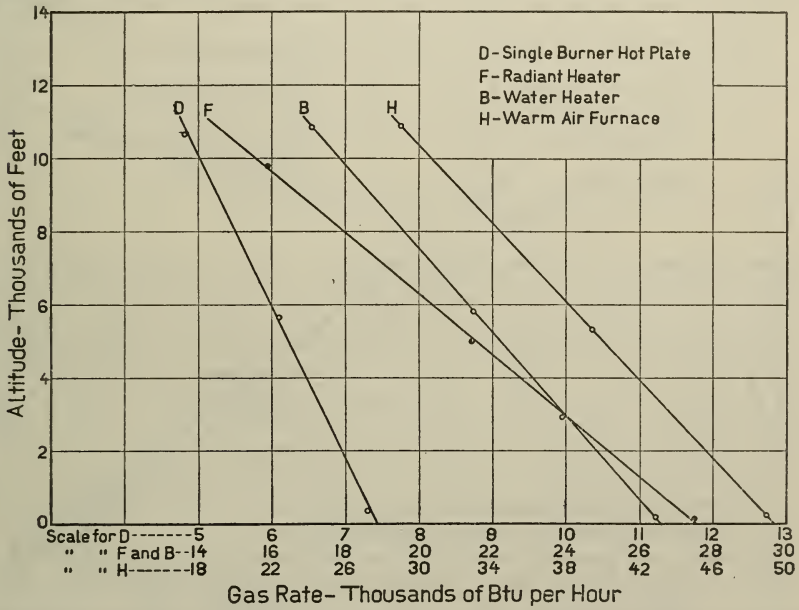

FIGURE 3.—*Straight-line relationship between altitude and the rate at which gas can be burned safely.*

The maximum gas rate which is safe at each altitude with 55 percent of the air required introduced as primary air is, of course, given by the intersection of the horizontal line representing 55 percent air and the "0 percent CO curve" for the same altitude.

These intersections for water heater *B* are replotted in figure 3, curve *B*, which shows that as the altitude is increased the maximum gas rate must be decreased if complete combustion is to be obtained. In terms of percentage, the maximum safe rate in B.t.u. per hour (at 55 percent primary air) which can be used at sea level is reduced 32.4

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[6] By the "total air required" for complete combustion is meant the amount of air which contains enough oxygen to combine with all the constituents of the fuel to form water and carbon dioxide. Some of the appliances encountered had burners which were incapable of injecting 55 percent of this air at gas pressures up to 5 inches of water. In these cases it was necessary to provide means for forcing the primary air into the burner in order that the data from all the appliances might be compared on the same basis. Attention is called to the recommendation in Bureau of Standards Circular No. 394 of details of construction which will permit the injection of as much primary air as possible, any undesired excess to be controlled by means of a shutter.

percent when the appliance is operated with the same air adjustment at 10,000 feet.

Although the points plotted represent data only for primary mixtures containing 55 percent of the air required for complete combustion, corresponding data for other primary mixtures of constant composition showed substantially the same reduction in safe rate, as the altitude was increased.

From curves for each appliance similar to those shown in figure 3, the safe rates in B.t.u. per hour at various altitudes have been computed as percentages of the safe rate at sea level and plotted in figure 4. The safe rate for each individual appliance is represented by a solid line. The average of all appliances except the radiant heaters was practically coincident with the curve representing appliances $I_0$ and *D*. This figure serves to indicate the variations between appliances of radically different mechanical construction, as well as the extent to which altitude affects the amount of gas that can be safely burned in a given appliance.

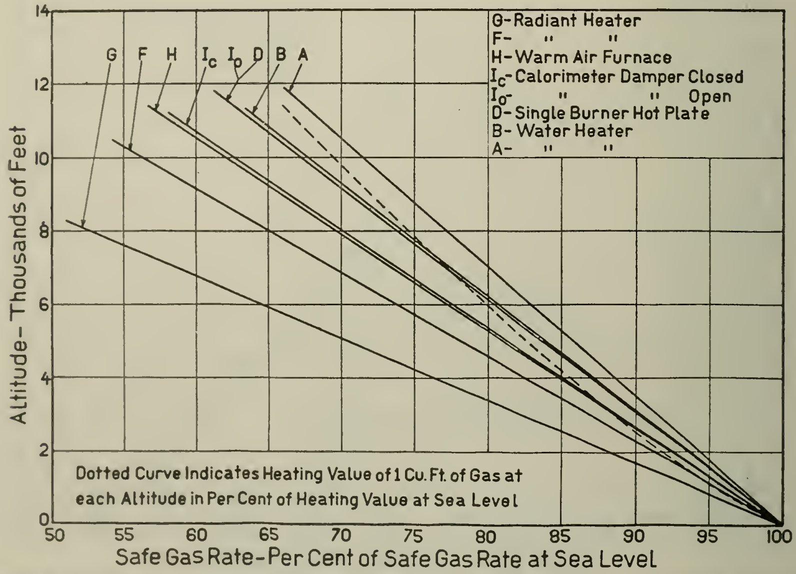

FIGURE 4.—*Effect of altitude on the safe gas rate compared on appliances differing greatly in design.*

Curves *D*, *F*, and *H* of figure 3 represent observed limiting rates for other appliances at which it is possible to burn the gas completely when the primary air supplied is 55 percent of that required for complete combustion. In each case the maximum safe rate when plotted against altitude yields a straight line within the limits of accuracy of the observations. In view of the varied character of these appliances, it seemed safe to assume that linear relations between maximum safe gas rate and altitude would also hold for other appliances. Thus the necessity of testing at more than two altitudes could be avoided.

Referring again to figure 4, a reduction of 4.0 percent of the safe rate (in B.t.u. per hour) at sea level for every thousand feet of altitude appears adequate in practice to protect the user from the hazard of incomplete combustion in all cases except those of the radiant heaters.

The peculiar hazard of radiant heaters together with the fact that the heaters of this type which were tested showed very large and decidedly different reductions in the safe rate with change of altitude, indicates that a very liberal factor of safety should be chosen for these appliances. Certainly, the safe rate at sea level should be reduced at least 6 percent per thousand feet unless a smaller reduction has been found sufficient by actual trial.

The heat of combustion of a cubic foot of a given gas changes in proportion to pressure. For an elevation of 10,000 feet it decreases about 3.1 percent per thousand feet. The change which takes place with changing altitude is shown by the broken line (fig. 4).

This reduction in B.t.u. per cubic foot is almost the same as the reduction in B.t.u. per hour required in the gas rate for the safe operation of most appliances except radiant heaters. It can, therefore, be readily seen that the average appliance will burn completely almost the same number of cubic feet per hour at one altitude as at another. This unexpectedly simple approximation can probably be used safely as a guide for the adjustment of appliances when they are known to have a fairly large margin of safety at sea level.

## V. EFFECT OF ALTITUDE ON THE "BLOW-OFF" AND "YELLOW-TIP" LIMITS

In addition to the change in the position of the curves representing the beginning of incomplete combustion, the effect of altitude on the position of the blowing and yellow-tip curves is also of interest. Referring again to figure 2, it will be observed that for a constant gas rate both blowing and yellow tips occur at lower primary air settings as the altitude is increased, although the effect on the position of yellow tips is small. Figure 5, obtained from figure 2, shows the effect of altitude on the primary air setting at which the flames blew from the ports when water heater *B* was operated at the normal gas rate specified by the manufacturer. For this appliance the reduction of primary air required to avoid blowing at 10,000 feet amounted to 14 percent of the total air required. When we consider that the range of safe adjustment lies between the blowing and yellow tip curves and to the left of the "0 percent CO curve" (fig. 2) it is evident that the range of safe adjustment is greatly reduced at an altitude of 10,000 feet.

If, instead of comparing the amounts of air which cause lifting of the flames when gas is supplied at the same rate (in B.t.u. per hour) at various altitudes, the rates of flow of the same primary mixture are compared, a simple relation appears. It is found that lifting occurs with any given primary mixture at an altitude of 10,000 feet at about 56 percent of the rate in B.t.u. per hour at which lifting occurs at sea level and that if the ratio of the rate at each altitude to the rate at sea level is plotted against barometric pressure a straight line results. Average data obtained from several appliances are plotted in figure 6. This figure also shows that the volume of the primary mixture passing through the port when lifting occurs at 10,000 feet is about 82 percent of that passing at sea level. The data obtained with several appliances at several air-gas ratios agree within the probable limits of error of observation.

From this figure and a lifting curve obtained at one altitude it should be possible to construct with fair accuracy the lifting curve

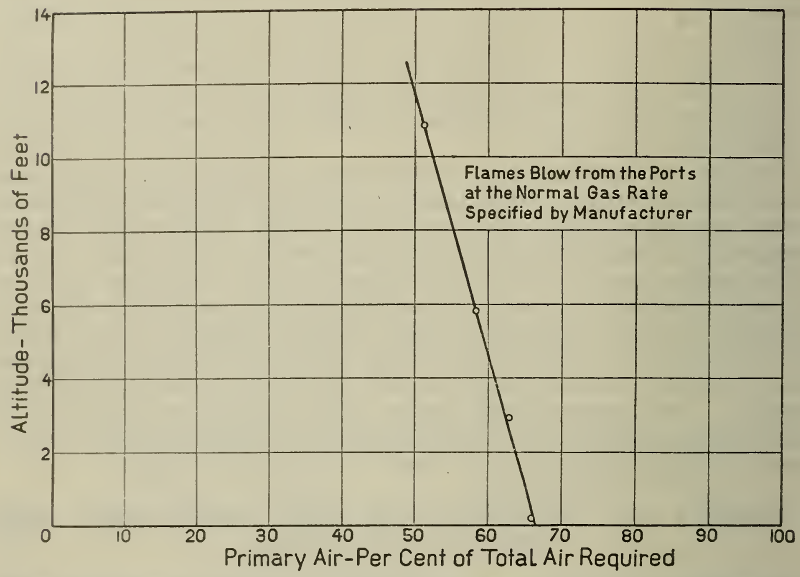

FIGURE 5.—*Effect of altitude on the primary air setting at which the flames blow from the ports.*

Water heater *B* operated at the normal gas rate specified by the manufacturer.

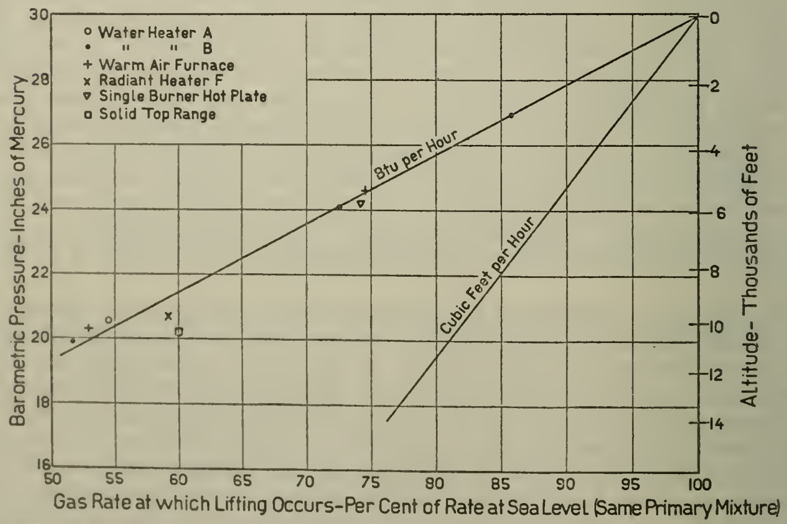

FIGURE 6.—*Effect of altitude on the gas rate at which lifting occurs with any given primary air setting.*

An average of five appliances.

for any other altitude, by making the indicated changes in the rate at which lifting occurs, for each of several primary mixtures.

## VI. EFFECT OF ALTITUDE ON THE AREA OF FLUE OPENING REQUIRED FOR A GIVEN GAS RATE

It was apparent at the outset that a reduction of the barometric pressure from 29.92 inches at sea level to 20.58 inches at 10,000 feet would cause the volume occupied by 1 cubic foot of gas at sea level to be increased to 1.45 cubic feet at 10,000 feet. Similarly, the air required to burn this gas would have its volume increased in the same ratio, and so would the total volume of products of combustion and excess air which must escape through the flue opening.

The supply of secondary air to the appliance and the escape of products of combustion from it depend on convection through its open passages; hence, of course, the amount of secondary air available for combustion depends on the resistance to flow through such passages. In a rigorous consideration of the convection through an appliance the air inlets, combustion space, and flue passages would have to be considered as a whole; but in many appliances the resistance to flow is mainly determined by the minimum cross section of the passages, and frequently the point of minimum cross section is at the outlet or "flue collar." The expenditure of time necessary for a thorough study of the convection through appliances at various altitudes did not appear to be justified, but it did seem desirable to make observations of the effects which could be simply produced by changing the size of the flue outlet.

A double gate was provided, sliding at right angles to the axis of the flue pipe, by means of which the area of the flue opening could be varied continuously from wide open to closed.

In a typical experiment, the primary air was set at 55 percent of the total air required, with the appliance operating near to, and sometimes slightly in excess of, the maximum safe gas rate. The area of the flue opening was then decreased by steps, and the carbon monoxide, carbon dioxide, and the temperature in the flue gases were determined at each step.

By plotting the area of the flue opening against the carbon monoxide produced, it was possible to determine the area of the opening at which combustion became incomplete. In some cases this involved a small extrapolation to a flue area larger than the appliance possessed. This process was repeated at each of several lower gas rates and at each of several altitudes. Figure 7, obtained from tests of this nature on water heater *B*, shows a curve for each of four altitudes,[7] from which the area of flue opening required for complete combustion at various gas rates can be obtained for this particular appliance.

For example, at a gas rate of 16,000 B.t.u. per hour the smallest area of flue opening which will permit complete combustion at an altitude of 200 feet is 1.5 square inches. In order to burn gas at this same rate at an altitude of 10,900 feet an area of 4.25 square inches is required. The areas required at different altitudes have been obtained in this manner from figure 7, for each of several gas rates, and plotted as

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[7] The curves have been drawn to intersect the horizontal line representing the "maximum" or unobstructed flue opening at points determined by the intersections, in figure 2, of the "0 percent CO curves" with the line representing 55 percent primary air. The observations by which these intersections were determined were entirely independent of and are believed to be more reliable than the observations which determined the other data represented in figure 7.

shown in figure 8. These curves show directly the effect of altitude upon the flue area required for complete combustion at any given gas rate. It is seen that, as the gas rate becomes higher, the area of flue opening required increases more and more rapidly with an increase in altitude. However, since each of the curves in figure 7 is approximately vertical at the maximum flue opening of 5.42 square inches, it is

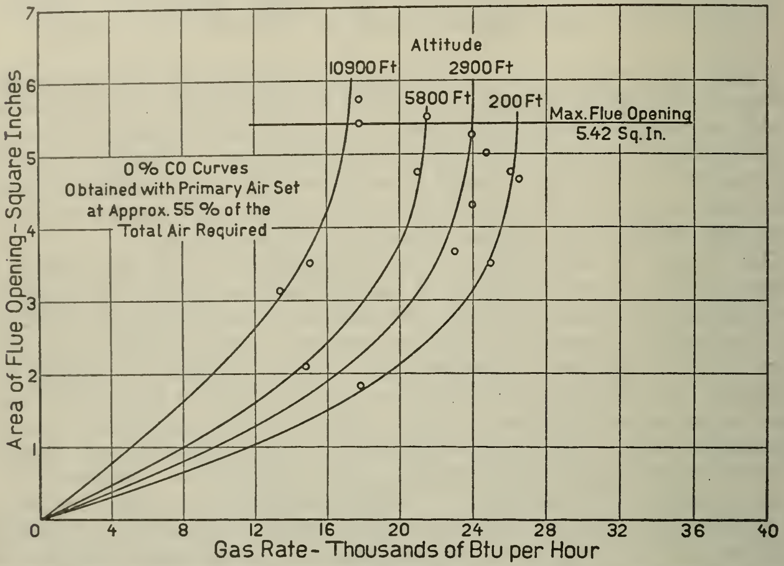

FIGURE 7.—*Effect of reducing the area of the flue opening of water heater B on the safe gas rate for various altitudes.*

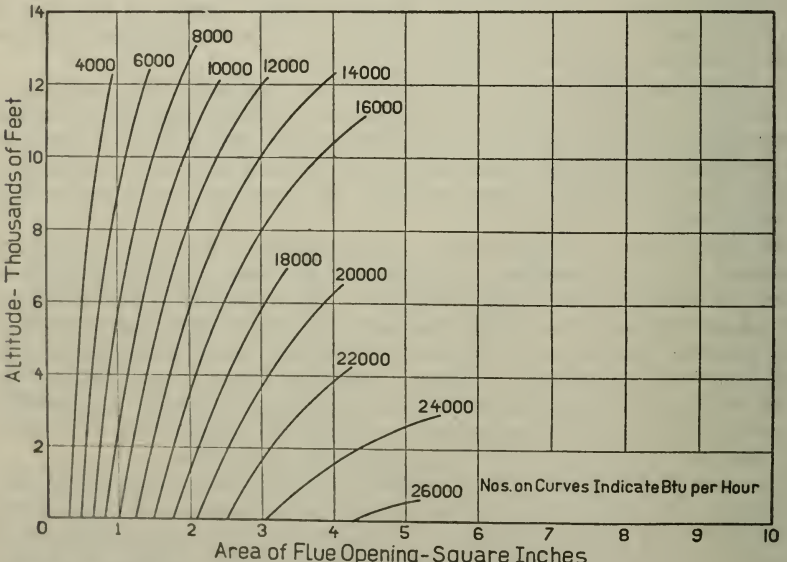

FIGURE 8.—*Effect of altitude on the area of flue opening of water heater B required for safe operation at various gas rates.*

evident that at no altitude would the safe capacity of this appliance be materially increased by enlarging the opening further. In other words, the safe capacity of this heater as it is built is limited by factors other than the area of the flue outlet.

Other appliances differ radically from this one with respect to the conditions which determine the relation between the area of the flue collar and the amount of gas that can be burned completely. The resistance to flow through the constriction at the flue collar may constitute almost the whole of the total resistance to flow through the appliance, or only a minor fraction of it. Incomplete combustion may result from the impingement of the flame on relatively cold surfaces under conditions which are nearly independent of the amount of excess secondary air. The secondary air may be so directed within the appliance that almost all of it, or only a part of it, comes into close contact with the flames and is thus available for supporting combustion. There are great differences in the height of the flue outlet above the burner and in the extent to which the products of combustion are cooled before reaching the outlet—factors that determine the draft "head" available to produce circulation. The problem is further complicated by the fact that many appliances have loose-fitting doors or other openings through which products of combustion escape to a certain extent when the vent is partially closed for purposes of study.

In spite of these differences, which might be expected to make impossible any useful generalization regarding the flueways of appliances, the data from five radically different appliances when plotted as in figure 8 gave series of curves so similar in character that, if not labeled, one set might readily be mistaken for any other.

When making quantitative comparisons between appliances of different sizes or types for the purpose of reaching general conclusions which may be of value to the designer, it is convenient to express the available data regarding the cross section of the flue in terms of square inches of flue area per 10,000 B.t.u. per hour, and the gas rate at which combustion becomes incomplete, as a percentage of the maximum safe rate, in B.t.u. per hour, at sea level. Curves plotted on this basis representing data from two appliances at two different altitudes and three other appliances near sea level are shown in figure 9. The curves representing water heater *B* are simply replotted on the new basis from figure 7, and those for the other appliances from corresponding curves representing their characteristics. It is again evident that the safe gas rate at high altitudes cannot be materially increased for either appliance *B* or *H* merely by enlarging the flue outlet; other parts of the appliance would have to be redesigned as well. From the curves representing conditions at approximately sea level it is apparent that the flue opening could be decreased without greatly affecting the maximum safe gas rate in the case of some but not all of the appliances. It is obvious that in no case, except possibly the warm-air furnace *H*, would further enlargement of the flue passages greatly increase the amount of gas that could be burned, unless other changes were made also. It is believed that the relatively large amount of gas that could be burned completely with very small flue outlets in appliances *A* and *E* was the result of leakage of flue gases through other openings.

For preliminary estimates by the designer of a water heater or other appliance in which all the secondary air passes close to a free-burning flame and the flue outlet is 2 feet or more above the level of the burner, it appears that 2 square inches of flueway per 10,000 B.t.u. per hour of maximum demand at sea level should be a satisfactory figure. This does not mean that an appliance having this area of flueway will necessarily be free from the hazard of incomplete combustion; still less does it mean that it will be safe to obstruct the larger flue of an appliance already built. What it does mean is that if a designer uses a flue of the size computed from this factor and finds that the appliance does not burn the desired amount of gas completely at sea level, any considerable improvement is to be sought from changes in other details of construction rather than from an increase in the size of the flue outlet. If the flue outlet is near the level of the burner, or the products of combustion are greatly cooled before rising much above the burner, or if the flames are partially confined, or impinge on relatively cold solid surfaces, the factor given cannot be expected to apply, but one must be chosen which is appropriate to the type of construction employed.

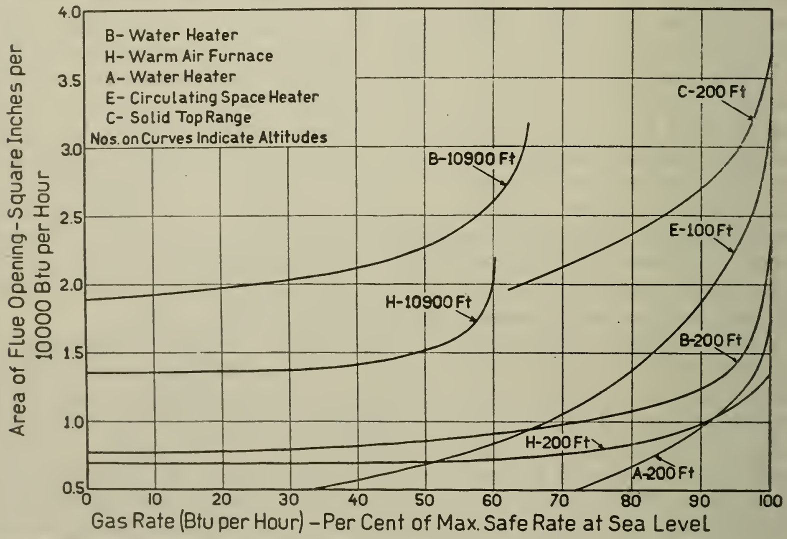

FIGURE 9.—*A comparison of the areas of flue opening required per 10,000 B.t.u. per hour for several appliances of different design.*

To construct an appliance for use at a high altitude, it must be designed as a whole to burn at sea level an appropriately greater quantity of gas. An example will serve to make the method clear. Assume that a water heater is to be designed to have a "normal" rating of 25,000 B.t.u. per hour in Denver at an elevation of 5,280 feet. Since an increase in gas pressure (above atmospheric) of at least 50 percent above that at normal adjustment must be provided for (American Gas Association requirement), the appliance must be designed to burn gas where installed at a rate of at least $25{,}000\times\sqrt{1.5}=30{,}600$ B.t.u. per hour. Allowing for a reduction in the safe gas rate of 4 percent per thousand feet of elevation (see sec. IV), the maximum safe rate at 5,280 feet is 79 percent of the safe rate at sea level.

The safe rate at sea level which should be allowed for is therefore

$$\frac{30{,}600 \times 100}{79} = 38{,}800$$

The flue area to be chosen for preliminary use in design is then $3.88 \times 2 = 7.76$ square inches.

## VII. EFFECT OF ALTITUDE ON THE TOTAL VOLUME OF FLUE GASES

In figure 10, curves are presented (from water heater *B*) showing the variation of the proportion of carbon dioxide in the flue gases with the gas rate, for each of four different altitudes, the primary air being held at 55 percent of the total air required.

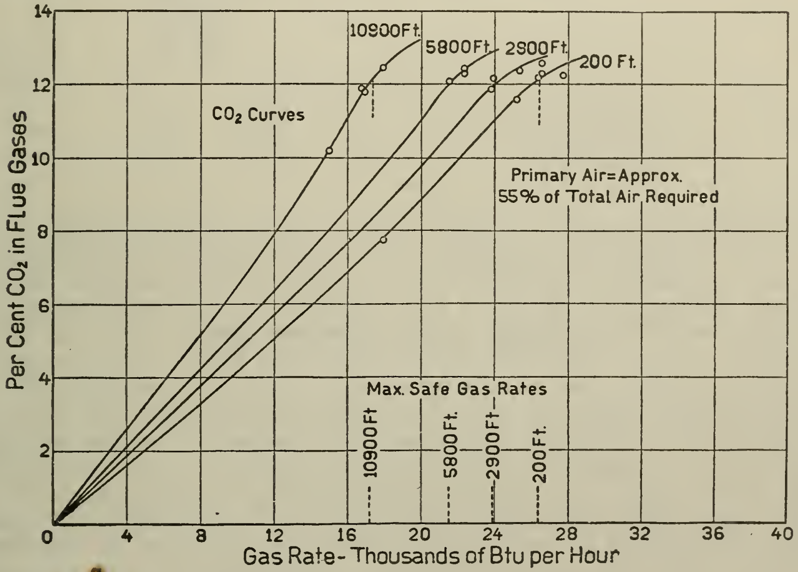

FIGURE 10.—*Relationship between the gas rate and the $CO_2$ content of the flue gases from water heater B at various altitudes.*

As can be seen from this figure, the concentration of carbon dioxide (at a given gas rate) increases as the altitude increases, or expressed in another way, a given concentration of carbon dioxide is obtained at a lower gas rate when operating at a higher altitude.

The broken lines in figure 10 indicate the gas rates above which carbon monoxide appeared in the products, for each of the four altitudes. When operating at an altitude of 200 feet, this gas rate is 26,400 B.t.u. per hour. Referring to the carbon dioxide curve for 200 feet, it is seen that at this gas rate the concentration of carbon dioxide was 12.1 percent. Similarly, at an altitude of 10,900 feet carbon monoxide appeared at a gas rate of 17,200 B.t.u. per hour, and the carbon dioxide concentration at this gas rate was also 12.1 percent. The same situation obtains at the other two altitudes.

Evidently, a carbon dioxide concentration of 12.1 percent is the highest obtainable with this appliance without incomplete combustion, irrespective of the altitude at which the appliance operates. This corresponds to excess air to the extent of 15.0 percent of the total air required, which is unusually low.

Similar curves for other appliances indicate that when combustion became incomplete the excess air had been reduced to definite although somewhat higher values. Table 1 shows the excess air present when combustion became incomplete in the cases of the four appliances tested which were capable of yielding this information.

Table 1.—*Carbon dioxide and excess air at the maximum safe gas rate*

| Appliance | $CO_2$ | Excess air at maximum safe gas rate; average for various altitudes. Percent of total air required |
|---|---|---|
| | *Percent* | |
| Water heater *B* | 12.1 | 15 |
| Warm air furnace *H* | 10.5 | 31 |
| Water heater *A* | 9.8 | 40 |
| Circulator *E* | 8.6 | 59 |

It was pointed out in section IV that the maximum safe gas rate in cubic feet per hour (not B.t.u. per hour) is nearly independent of altitude, at least for the most numerous class of flue-connected appliances. Since the volume of the products of combustion bears a constant ratio to the volume of gas burned and can be computed from analysis (1 cubic foot of the mixed gas used in the investigation produced 5.12 cubic feet of products), the volume of products at the maximum safe gas rate is also nearly independent of altitude. It has just been shown that the percentage of excess air in the flue gases at the limit of complete combustion is independent of altitude within the limit of observation, and all these facts taken together lead to the following roughly approximate relationship: If an appliance is moved from one elevation to another, the maximum safe gas rate in cubic feet per hour (measured at local barometric pressures) and the corresponding volumes of primary air, secondary air, products of combustion, and flue gases will remain approximately unchanged.

The rule is to be used only as an approximation. There are important departures from it which have been discussed in section IV.

A mental picture of what happens in the typical appliance may be had by considering the products of combustion as occupying an increasing proportion of the total capacity of the flue passages as the gas rate is increased, while the amount of secondary air which enters the appliance does not increase in proportion, and finally becomes insufficient to complete the combustion of the gas.

The constant excess of secondary air present in the flue gases in a given appliance when this condition is reached may be regarded as a measure of the efficiency of application of the secondary air.

## VIII. EFFECT OF ALTITUDE ON THE INJECTION OF PRIMARY AIR

The top burner of a range was set to deliver approximately 9,000 B.t.u. per hour at 3½ inches pressure, and the primary air was adjusted to about 55 percent of the total air required, while operating at sea level. Leaving the orifice and air shutter as set, the altitude was changed to 10,400 feet, and the gas pressure reset at 3½ inches. The result was to change the gas rate from 8,970 B.t.u. per hour to 7,190 B.t.u. per hour, a decrease of 780 B.t.u. per hour. The percentage of primary air injected was not affected.

When the gas rate was restored to approximately 9,000 B.t.u. per hour (9,120), however, the gas pressure required rose to 5½ inches. The resulting effect on the composition of the primary mixture was again negligible.

When the orifice was adjusted to deliver 9,150 B.t.u. per hour at the normal pressure of 3½ inches, as it had done at sea level, the primary air injected fell from 54 percent to about 47 percent as it might be expected to do when the size of the orifice is increased.

The net result of the change of altitude, then, if the burner delivers the same number of B.t.u. per hour at the same gas pressure without a readjustment of the air shutter, is to decrease the primary air injected from 54 to 47 percent, which is of no great significance with most appliances, since the difference is not easy to detect from the appearance of the flames, and the original amount of air injected can usually be restored by opening the air shutter.

## IX. EFFECT OF ALTITUDE ON THE EFFICIENCY OF A TOP BURNER OF A RANGE

The efficiency of a top burner of a gas range was determined in the manner described in Research Paper No. 446.[8] The burner was operated at sea level, and again at an altitude of 10,400 feet, at its normal rate of 9,000 B.t.u. per hour with the primary air set at approximately 55 percent of the total air required. Two efficiency determinations were made at sea level, two at 10,400 feet, and one more on returning to sea level. The results are presented in table 2.

TABLE 2.—*Effect of altitude on the efficiency of a top burner*

| Test No. | Gas rate | Primary air, percent of total required | Altitude | Efficiency | Average |
|---|---|---|---|---|---|
| | *B.t.u./hr.* | | *Feet* | *Percent* | *Percent* |
| 1 | 9,120 | 53.8 | 0 | 31.2 | |
| 2 | 9,120 | 54.9 | 0 | 30.5 | 31.0 |
| 9 | 9,000 | 54.1 | 0 | 31.2 | |
| 7 | 9,150 | 53.6 | 10,400 | 33.2 | 33.2 |
| 8 | 9,090 | 53.2 | 10,400 | 33.1 | |

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[8] See footnote 3, p. 620.

It appears that at the higher altitude the efficiency is slightly increased. This may be accounted for by a slightly better contact between flame and utensil at this particular distance between the burner and the utensil, which on this range was 2¼ inches. From considerations developed in Research Paper No. 446 [9] it is probable that the effect upon efficiency might be in either direction, depending upon the original adjustment of the burner. Variations in excess of 2 or 3 percent are not uncommon under normal operating conditions and, therefore, the variation obtained in this test cannot be assumed to be of much significance.

## X. EFFECT OF ALTITUDE ON THE OPERATION OF PILOTS

Pilot flames may be divided into two general classes, those which are aerated (blue flame) and those which are unaerated (yellow flame).

A blue-flame pilot will be affected by altitude in exactly the same manner as the flame on any of the ports of the burner of an appliance and its behavior has therefore been covered by the foregoing discussion of the effects of altitude on the various characteristics of the main burners.

For example, the ratio of primary air to gas, in a blue-flame pilot of fixed mechanical construction, will be practically unaffected by altitude. It may also be assumed that the ratio does not change with the gas pressure (the fall of pressure through the orifice). The volume of gas delivered through a fixed orifice at a given gas pressure varies inversely as the square root of the density of the gas, and, of course, the volume of the primary mixture of constant composition varies in the same ratio. From these relations the relative volumes of primary mixture delivered at the same gas pressure at sea level and at any other altitude may be computed from the corresponding barometric pressures. From figure 6 the relative volumes of primary mixture which cause lifting at the two altitudes may be ascertained and by combining these facts with the well-known relation between the flow of gas and the fall of pressure through an orifice the relative gas pressures at which lifting will occur at the two altitudes may be easily found. A numerical example will make the method clear.

Assume that a blue-flame pilot is to be constructed, tested, and provided at sea level with a fixed orifice and primary air opening which will insure that it will be safe from lifting in Denver at a gas pressure of 15 inches. The case assumed to illustrate all the relations involved is an extreme one in that no adjustment whatever is provided for. The relative barometric pressures in Denver and at sea level are in the ratio of $\frac{24.6}{29.9}$ and the densities are in the inverse ratio. Hence, the volume of gas delivered through the fixed orifice in Denver will be

$$\sqrt{\frac{29.9}{24.6}}=1.10$$

times the volume delivered at sea level.

From figure 6 it is found that the flame will lift in Denver when the velocity of flow of the primary mixture is about 90 percent of that at

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[9] See footnote 3, p. 620.

sea level. Hence, if lifting is to be avoided in Denver, the number of cubic feet per hour which the fixed orifice is to pass at sea level must not be greater than the fraction

$$\frac{0.90}{1.10}=0.82$$

or 82 percent of the rate which causes lifting at sea level. This limiting ratio may be arrived at experimentally by making use of the pressure relation. The rate at which gas is delivered through an orifice is proportional to the square root of the fall of pressure through the orifice, or stated in another way, the pressure is proportional to the square of the gas rate; hence, the flame must not blow from the port at sea level at a gas pressure less than

$$\frac{100}{82}\times\frac{100}{82}=1.5$$

times the pressure to be encountered in Denver, or a total of $15\times1.5=22.5$ inches.

To operate safely, a pilot must not only be safe from blowing off at the highest pressure likely to be encountered; it must also ignite the gas with certainty at the lowest pressure. It was observed that the length of a flame supplied with a primary mixture of given composition is dependent upon the total number of B.t.u. supplied and varies but little with altitude. Hence, to be safe at a high altitude, the pilot light should ignite the gas at sea level at the lowest rate in B.t.u. per hour likely to be delivered at the higher altitude. Since the volume of gas delivered at a definite gas pressure is inversely proportional to the square root of the barometric pressure, and the heating value per unit volume is directly proportional to the barometric pressure, the number of B.t.u. per hour delivered through a fixed orifice is proportional to the square root of the barometric pressure. Thus, in Denver, the number of B.t.u. per hour delivered through a fixed orifice is the fraction

$$\frac{24.6}{29.9}=0.908$$

or 90.8 percent of the heat delivered at sea level. To give the same rate in B.t.u. per hour the gas pressure at sea level must be the fraction

$$0.908\times0.908=0.833$$

or about 83 percent of that in Denver. If we assume that to be safe in Denver the pilot light must assure ignition at 1.5 inches pressure, it should cause ignition at sea level with 83 percent of 1.5 inches, or 1.25 inches pressure. Hence, to insure safety in Denver at all gas pressures between the extreme limits assumed, 1.5 and 15 inches, the pilot light should be tested at sea level between 1.25 and 22.5 inches.

A yellow-flame pilot burns gas with no admixture of primary air, and tests were necessary to determine the extent to which altitude would affect flames of several given heights burning on ports of different sizes. For these tests both the mixed gas of the city supply and propane were used.

The gas rate and corresponding height of flame were determined for two sizes of port (no. 66 and no. 48, drill manufacturers' standard) at sea level and at 9,900 feet, in one case with a flame about 2 inches high, and in another case at the gas rate at which the flame blew away from the port. The height of each flame was plotted against the gas rate, and all the points fell very close to a single straight line for flames up to 6 inches high. This indicates that, for all practical purposes, the height of an unaerated gas flame from a small opening such as is used for a pilot light is determined by the gas rate in B.t.u. per hour, regardless of altitude, size of port, or the kind of gas used.

The velocity of the gas stream was computed in the cases in which the flame blew away from the port. With a given gas and port size, the velocity required appeared to be independent of the altitude. With the mixed gas the velocity required was about the same for the two port sizes, but with propane it was slightly greater for the smaller port. The average velocity of the gas stream (both ports and both altitudes) required to blow the flames from the ports was 4.7 times as great for the mixed gas as for propane.

The flame which lifted most easily was that of propane, at the highest altitude, on the smallest port. It had a height of 6 inches, which is at least three times that needed for most pilots. This indicates that lifting from the port is not likely to be a source of difficulty at high altitudes any more than at sea level.

## XI. EFFECTS OF ALTITUDE COMPARED ON TWO DIFFERENT GASES

In the case of the manually operated calorimeter, the primary air was set just high enough to eliminate yellow tips from the flame[10] and the maximum safe B.t.u. rate determined with the flue damper both in the open and in the closed position. This was done at sea level and at an altitude of 10,000 feet, using mixed gas and propane. Table 3 summarizes the results.

TABLE 3.—*A comparison of the effects of altitude with different gases*

| Gas | Maximum safe gas rate (B.t.u. per hour) | | | | Altitude, feet |
|---|---|---|---|---|---|
| | Damper open | | Damper closed | | |
| | Gas rate | Percent reduction per 1,000 feet | Gas rate | Percent reduction per 1,000 feet | |
| Mixed gas | 8,400<br>5,625 | 3.29 | 5,060<br>3,175 | 3.73 | 0<br>10,000 |
| Propane | 8,400<br>5,600 | 3.33 | 4,975<br>3,025 | 3.90 | 0<br>10,000 |

The results indicate that the maximum safe gas rate, at a given altitude, with the damper open, was almost exactly the same with both gases.

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[10] This is the primary air setting recommended for use with calorimeters of this type (see p. 66 B.S. Circular no. 48, Standard Methods of Gas Testing), and corresponds to about 30 percent of the total air required. In the case of propane the flame was slightly yellow, and the mixture contained about 25 percent of the total air required.

With the damper closed, the maximum safe gas rate at both altitudes was about 100 B.t.u. per hour less with propane than with mixed gas. The reduction of the maximum safe B.t.u. rate at sea level required for each thousand feet of altitude is also about the same for the two gases.

It therefore seems probable that the effect of changes of altitude with other appliances will not be very different for gases of different compositions.

## XII. SUMMARY AND CONCLUSIONS

Nine gas appliances of distinctly different design were studied, and the effects of altitude on the limits of safe operation were found to be nearly the same for all of the appliances tested, with the exception of radiant heaters, which appeared to be more affected than other appliances. Excepting the radiant heaters, the maximum safe gas rate, in B.t.u. per hour, is reduced between 3 and 4 percent of the safe rate at sea level each thousand feet of elevation.

It is a simple but only roughly approximate general rule that an appliance, adjusted to take the same ratio of primary air to gas at two altitudes, can, without other adjustment, burn completely the same number of cubic feet of gas per hour at both altitudes. It will also receive the same volume of primary and of secondary air and will deliver the same volume of flue gases of the same composition at both altitudes. All of these volumes are as measured at the local barometric pressure at each altitude.

To construct an appliance for safe use at a high altitude, it must be designed as a whole to burn safely at sea level an appropriately greater quantity of gas. Some data are given from which preliminary estimates may be made of the necessary size of flue passages for certain types of appliances.

The effect of a change of altitude on the injection of primary air is not great enough to be detected from the appearance of the flames.

Unaerated or yellow-flame pilots are unaffected by changes in altitude, unless they are "smothered" by products of combustion from the main burner.

At the normal rate in B.t.u. per hour specified by the manufacturer, the percentage of primary air required to make the flames lift from the ports is reduced for each thousand feet of elevation by about 1.25 percent of the total air required. The rate at which a given mixture of gas and air can be delivered from a port without causing the flame to lift is reduced about 4.5 percent per thousand feet of altitude if rates are expressed in B.t.u. per hour, or about 1.75 percent if they are expressed in cubic feet per hour.

The effect of altitude on the efficiency of the top burner of a range was negligible.

The temperature of the flue gases has little relation to the altitude, but is almost entirely a function of the rate in B.t.u. per hour.

The effect of altitude in reducing the amount of gas that can be burned completely in a calorimeter was found to be the same with propane as with mixed city gas. It is concluded that the effects would have been the same had the comparison been made with other appliances or other gases.

WASHINGTON, January 28, 1933.