efficiently utilizing our fuel supplies cannot be completely measured. It would be extremely difficult to make individual acknowledgments to all who have contributed to this program. The voluntary cooperation of both industrial and domestic users of fuels has been especially gratifying. Representatives of various industries, commercial plants, technical societies, and Government agencies have contributed their individual and cooperative efforts in making the program a success.

Mixtures of Coal and Oil

Emergency use of mixtures of pulverized coal and fuel oil, popularly called "colloidal fuel," in existing oil-burning equipment would save about one-third the available oil and would reduce the required amount of additional costly coal-burning equipment. Conversion of oil-fired boilers to "colloidal" fuel firing was found to be possible without great change in average boiler-plant construction or appreciable difference in boiler efficiency as compared with use of Bunker C fuel oil.[61] Results are reported on the operation of a typical boiler installation during cooperative tests conducted for 1 month by Bureau engineers and the Atlantic Refining Co. The fuel used was a mixture of 40 percent pulverized bituminous coal by weight and 60 percent No. 6 (Bunker C) fuel oil. No "fixateur" or stabilizer was added, and no particular trouble was experienced in batch mixing of the coal and oil. Operations as affected by increased suctions, pressures and loadings on the pumps, abrasiveness of the fuel, settling of coal from the mixture, and ash deposition in the furnace were studied, and no unsurmountable difficulties were encountered.

Extensive laboratory and field tests on the stability of coal suspensions in fuel oil showed that individual consideration must be given to each installation using this mixed fuel, if satisfactory tests are to be obtained.[62] However, no particular difficulty should be experienced in devising equipment or in routine operating to use efficiently this mixed fuel. The study showed that for practical purposes a sufficiently stable

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[61] Barkley, J. F., Burdick, L. R., and Hersberger, A. B., "Colloidal" Fuel Substituted for Oil Fuel: Nat. Petrol. News, Tech. Sec., vol. 35, July 1943, pp. R-304-306. "Colloidal" Fuel for Oil: Steel, vol. 113, July 1943, pp. 98-99, 137-138. "Colloidal" Fuel Tests Show Possibilities as Oil Substitutes: Coal Age, vol. 48, July 1943, pp. 51-53. Tests Reveal Colloidal-Fuel Performance: Power, vol. 87, August 1943, pp. 72-73, 144, 146, 148, 150, abs., Steam Eng., vol. 13, January 1944, pp. 104-107.

[62] Barkley, J. F. Hersberger, A. B., and Burdick, L. R., Laboratory and Field Tests on Coal-in-Oil Fuels: Trans. Am. Soc. Mech. Eng., vol. 66, 1944, pp. 185-196; discussion, pp. 196-198. Tests on Coal-in-Oil Fuels: Power Plant Eng., vol. 48, January 1944, pp. 82-84, 132, 134 136, 138. Abs., Power, vol. 87, December 1943, pp. 178-182; Steam Eng., vol. 13, June 1944, pp. 259-263.

suspension could be prepared by dispersing 40 percent of coal by weight, ground to pass 98 to 99 percent through a No. 230 sieve, in heavy fuel oil. Careful control of storage and handling temperatures is necessary for best operation. The pumping of coal-in-oil suspensions, particularly from underground storage tanks, requires special attention. The combustion efficiency of coal-in-oil fuel is likely to be slightly less than that of fuel oil; their load-carrying flexibilities are about the same. The report covers technical information and does not take up the varying economic comparison involving relative costs of coal and oil.

Utilization of Small-Size Anthracite

In allocating fuel supplies for the Nation, the Solid Fuel Administration for War found that a growing surplus of small sizes of anthracite at the collieries was hindering the production of much needed domestic-size anthracite. Following a meeting of representatives of the anthracite industry, the Solid Fuels Administration for War, and the Bureau of Mines, a program was initiated to remedy this situation and at the same time to alleviate the general coal shortage through increased uses of anthracite fines. Tests were made at a number of plants on the burning of various mixtures of barley-size (No. 3 Buckwheat) anthracite and slack-size bituminous coal on underfeed stokers. The tests included many made in cooperation with the War Department in boiler plants at military camps in the eastern states, for other Government agencies, and in privately owned plants. A discussion[63] of typical results obtained at several plants was published. Chief advantages found by adding barley anthracite to bituminous slack burned on single-retort stokers were: (1) A reduction of coking troubles caused by certain eastern bituminous coals and (2) a lessening of the air-pressure drop through the fuel bed. At one plant as much as 80 percent of anthracite gave satisfactory operation and carried the required load; at another plant a 50-percent addition gave the best performance. Increasing additions of anthractie resulted in hand-working the fuel bed being reduced. For low-ash bituminous coals, lower percentages of anthracite gave better results; the higher percentages gave less flexibility on load changes and lower ratings. For higher-ash bituminous coals, higher percentages of anthracite could be used satisfactorily in obtaining similar loads. Combustible in the refuse and the fly ash was increased, and the volume of smoke produced was decreased by the use of anthracite. In general, the efficiencies obtained on single-retort stokers with various percentages of added anthracite were about the same as with straight bituminous coal. The better fuel-bed conditions due to anthracite are offset to some extent by the increase of combustible in the ash and refuse. Further details of the results of burning tests of mixtures of anthracite and bituminous coal were published.[64] This paper also presents the technical aspects of this and

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[63] Barkley, J. F., Discussion of "The Combustion of Barley Anthracite," by Allen J. Johnson: Trans. Am. Soc. Mech. Eng., vol. 66, 1944, p. 406.

[64] Barkley, J. F., and Seymour, W., The War Problem of Increasing the Utilization of Small Anthracite: Preprint of paper presented at semiannual meeting, Am. Soc. Mech. Eng., Fuels Division, Pittsburgh, Pa., June 20, 1944, 11 pp. (mim.).

three other projects. These three latter projects are still in progress; they include studies of (1) methods of producing and burning "packaged fuel" made from anthracite fines, (2) use of anthracite fines as a substitute for part of the low-volatile bituminous coal used in coke-oven charges, and (3) use of barley-size anthracite in gas producers.

Supplementing Anthracite with Other Fuels for Home Heating

Studies of emergency fuels for home heating were made under controlled laboratory conditions closely duplicating those occurring in domestic heaters. The fuels tested included reclaimed beehive coke, mixtures of anthracite and bituminous coal, and packaged fuels made from anthracite fines. Suitability of the emergency fuel was determined from the standpoint of rate of burning, draft required, tendency to produce smoke, caking characteristics, and ash content. Domestic consumers unable to obtain their usual supplies of anthracite were advised to substitute bituminous coal in part, and methods of firing the composite fuel were described.[65] Brief summaries of methods for reducing clinker formation and removing soot accumulations were included.

Studies of Packaged Fuel

A report[66] was published that reviewed the status of the packaged-fuel industry as of 1941. A field study was made of 35 representative plants to obtain technical and economic data on the different types of processes used to make packaged fuel in the Central States. The report includes a classification of processes, photographs of typical operations, designs of different plants, an analysis of costs of manufacture, and a study of the physical and chemical properties of the fuel cubes or bricks. As distinguished from fuel briquets, packaged fuel, although briquetted, is wrapped in paper and differs in methods of manufacture and handling and in shape and size. It is generally made in relatively smaller plants located near the ultimate consumer, and more care must be used in its handling and distribution than with fuel briquets. These fundamental differences between the two types of briquetted fuel are reflected in the costs and economics of the two industries. Many of the packaged-fuel plants had trouble in competing with lump coal under the conditions of costs of materials and labor existing in 1941-42. Predominant technical difficulties in plants were found to be due to inadequate drying and insufficient mixing of the binder. Laboratory studies showed the relationship between the temperature of dry air and the time required to remove different percentages of moisture in wrapped and unwrapped coal cubes. The average physical and chemical properties of fuel cubes made by five processes were determined. Tentative standards for minimum physical qualities and methods for measuring quality were suggested. A satisfactory packaged fuel, air-dried to about 1.0 percent moisture content, should have an average compressive strength of not

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[65] Reid, W. T., Supplementing Anthracite with Other Fuels for Home Heating: Bureau of Mines Inf. Circ. 7260, 1943, 22 pp.

[66] Parry, V. F., Technical and Economic Study of Packaged Fuel: Bureau of Mines Rept. of Investigations 3757, 1944, 45 pp; Min. Cong. Jour., vol. 30, November 1944, pp. 24-27.

less than 85 pounds per square inch and an apparent specific gravity of not less than 1.04, and the average abrasion loss in a modified tumbler test for coal should not exceed 15.0 percent. Packaged fuel has proved to be a satisfactory domestic fuel in many cities. Considerable expansion of possible market is indicated for good, solid cubes delivered in clean, dry packages, even at premium prices above that of lump coal delivered in bulk. The fuel has been particularly popular for spring and fall heating. Some changes in firing technique with no distrubance or poking until the cube has been thoroughly heated and coked on the outside were recommended.

Automatic Stoker for Heating Water

A new-type stoker and heater for supplying hot water automatically was developed and tested. The unit has operated satisfactorily for 2-1/2 years, with a consumption of about 300 pounds of selected coal a month. Several grades of subbituminous coal have been burned successfully, with a thermal efficiency of about 71 percent.

Properties of Coal Ash as Related to Clinkering and Slagging

Data not previously available on the flow properties of coal-ash slags below the temperature where crystals separate from the melt on cooling were obtained in a recent study.[67] The conventional concentric-cylinder viscometer used in a previous study was modified to include a motor drive; a reducing atmosphere was used to control the oxidation of iron forms in the slag. The study showed that the "temperature of critical visosity," where the flow of slag changes abruptly from liquid to plastic flow on slow cooling, was affected in a complex manner by change in composition and state of reduction of the forms of iron present. For a given state of oxidation, the temperature of critical viscosity, T_{cv}, decreased as the equivalent ferric oxide content of the slag increased, this being greatest for small amounts of calcium oxide. For a fixed ferric oxide content, increasing calcium oxide also decreased T_{cv}. Decrease in the ferric percentage lowered T_{cv} most as the equivalent ferric oxide content of the slag increased. Similar complex relationships were found to exist for the freezing temperature of coal-ash slags. The viscosity-temperature relationship at temperatures high enough for the slags to be completely in the liquid state was represented by the equation:

$n^{z} = A\,t - B$, where n is viscosity in poises, z is 0.1614, A is 0.0004519, t is degrees Fahrenheit, and B is a constant depending on the composition of each slag. Figure 5 is a nomogram based on this relationship; it allows estimation of the viscosity of coal-ash slags at any temperature above T_{cv}. Application of determined date in predicting the relative thickness of various slag deposits, although based on idealized furnace conditions, will prove useful in proposed field studies of the action of coal-ash slag in furnaces. A recent paper[68] was published giving complete details of this

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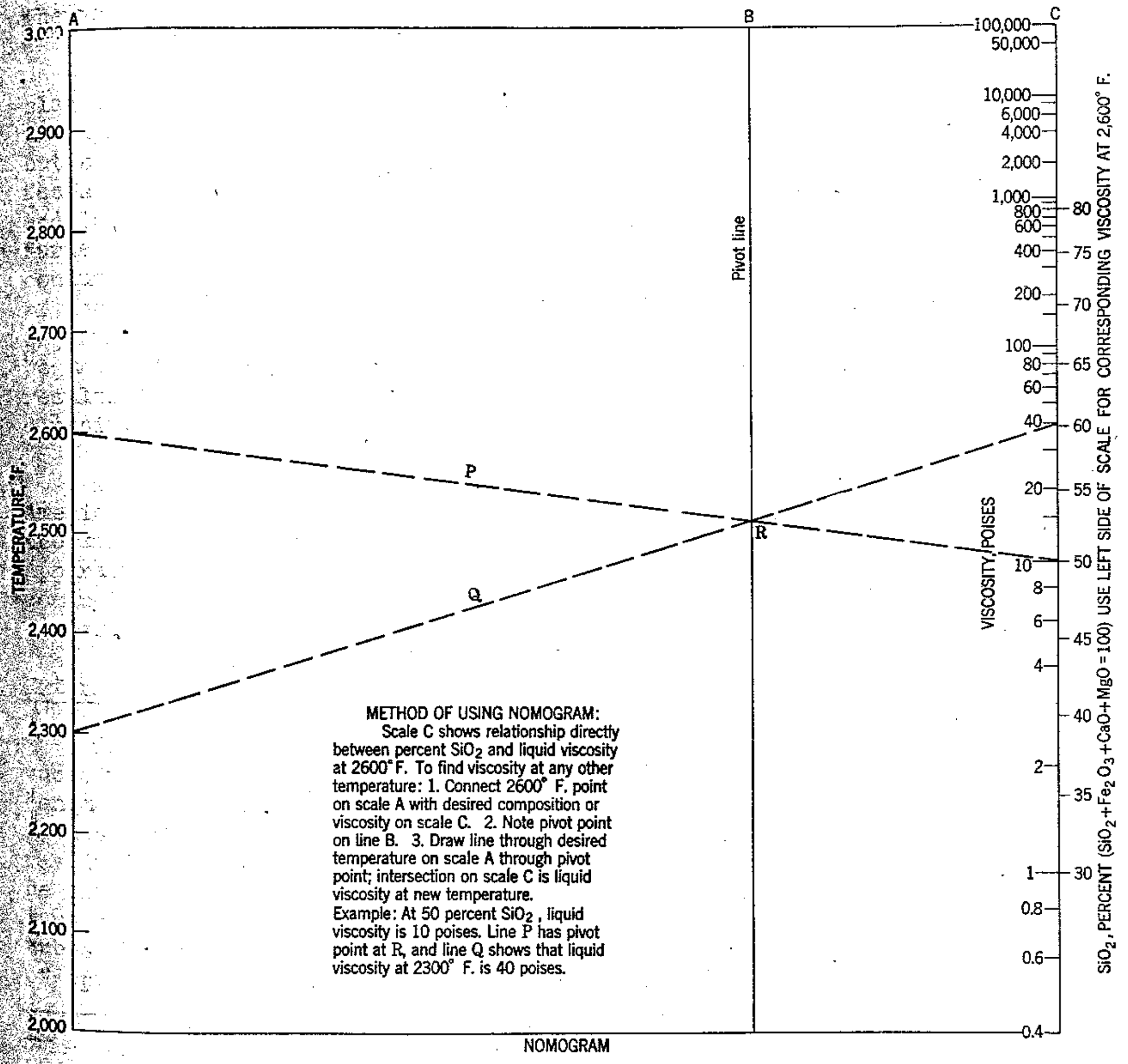
[67] Reid, W. T., and Cohen, P., The Flow Characteristics of Coal-Ash Slags in the Solidification Range: Am. Soc. Mech. Eng., Furnace Performance Factors (pamphlet), May 1944, pp. 83-97.

[68] Cohen, P., and Reid, W. T., The Flow of Coal-Ash Slag on Furnace Walls: Bureau of Mines Tech. Paper 663, 1944, 22 pp.



METHOD OF USING NOMOGRAM:

Scale C shows relationship directly between percent SiO_2 and liquid viscosity at 2600° F. To find viscosity at any other temperature: 1. Connect 2600° F. point on scale A with desired composition or viscosity on scale C. 2. Note pivot point on line B. 3. Draw line through desired temperature on scale A through pivot point; intersection on scale C is liquid viscosity at new temperature.

Example: At 50 percent SiO_2, liquid viscosity is 10 poises. Line P has pivot point at R, and line Q shows that liquid viscosity at 2300° F. is 40 poises.

FIGURE 5.- Viscosity of coal-ash slags in the liquid state as a function of composition and temperature.

method for calculating the thickness of slag deposits and illustrations were given of its application to slagging furnaces. A field study on the action of coal ash in boiler furnaces has been planned in cooperation with the Special Research Committee on Furnace Performance Factors of the American Society of Mechanical Engineers.

Thermal Conductivity of Coal-Ash Slags

Methods have been suggested[69] whereby the physical condition of the slag deposit can be used as a rough measure of the rate of heat transfer through the slag. Direct measurements of this factor would be preferable but suitable devices for measuring the rate of heat transfer to slagged surfaces in operating furnaces must be used with forethought as to their design and location in the furnaces.[70] In the problem of heat transfer from the furnace cavity to the tube metal, allowance must be made for the thermal conductivity of the slag and the thermal resistance of the interfacial layer of loose ash between the tube metal and the slag. This thermal resistance is difficult to measure. The thermal conductivity of the slag itself can be measured directly in the laboratory under controlled conditions and the results applied to field tests to determine the over-all conductivity of the deposit.

In cooperation with the Furnace Performance Factors Committee of the American Society of Mechanical Engineers, a laboratory investigation of the thermal conductivity of coal-ash slags at high temperatures was begun. Apparatus has been designed and tests have been started to measure the thermal conductivity for temperatures ranging from 1,800° to 2,800° F. and for compositions representative of normal coal-ash slags.

External Corrosion of Furnace-Wall Tubes

The mechanism of reactions causing external corrosion of furnace-wall tubes was investigated further. The mode of formation of the greenish white "enamel" found in or adjacent to corrosion areas was studied by comparison with synthetically produced material whose composition was identified by X-ray diffraction analysis. Under certain conditions the enamel was shown to be highly corrosive. Attempts to measure by radiometric methods the temperature of the thin oxide film occurring on the surface of the furnace-wall tubes showed that certain important considerations must be given to the use of optical and total radiation pyrometers.[71] The study showed that under

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[69] Reid, W. T., Discussion of "Studies of Heat Transmission Through Boiler Tubing at Pressures from 500 to 3300 Pounds," by W. F. Davidson and others: Trans. Am. Soc. Mech. Eng., vol. 65, 1943, pp. 589-590.

[70] Reid, W. T., Discussion of "Distribution of Heat Absorption and Factors Affecting Performance of Twin Branch 2,500-Psi Boiler" by F. G. Ely, and L. B. Schueler: Am. Soc. Mech. Eng., Furnace Performance Factors (pamphlet), May 1944, pp. 30-31.

[71] Reid, W. T., and Corey, R. C., Errors in Temperature Measurements by Radiometric Methods: Combustion, vol. 15, February 1944, pp. 30-34.

conditions where the object has a temperature lower than the surroundings, as in the case of furnace tubes absorbing heat, small variations in emissivity radically affect the temperature observed by the optical pyrometer but have appreciably less effect on the total radiation pyrometer. Tables showing the apparent temperatures of cold objects surrounded by an environment at 2,700° F. were provided to show comparisons between the two types of instruments.

Burning Solid Fuels on Traveling Grates

Tests of the burning characteristics of various ranks of coal on traveling- or chain-grate stokers were continued with a high-volatile C bituminous coal from Illinois and a raw lignite from North Dakota.

Less variation in rate of ignition travel was observed with change of size of the high-volatile C bituminous coal than had been found with higher-rank coals and coke. Ignition rates were relatively high over a very wide range of air rates, but they showed a tendency to decrease at 600 pounds per square foot per hour and higher air rates. Less difficulty was experienced with caking and poor-air distribution at the lower air rates than had been found previously with more highly caking Pittsburgh-bed, high-volatile A bituminous coal. At air rates of 400 pounds per square foot per hour and higher, ignition and burning were obtained with relatively little caking.

With lignite, no gain in rate of ignition travel was indicated for the use of air rates exceeding 250 pounds per square foot per hour for the raw lignite, although no sharp drop in ignition rate is indicated at air rates up to 600 pounds. This is a very reactive fuel and burns with very thin burning layers. Excessive loss of heat from such burning layers, as when exposed to cold furnace walls, will materially reduce the rate of ignition and burning in such thin layers. Highest ignition and burning rates would therefore be expected with this fuel in refractory-lined furnaces with walls at high temperature.

Reactivity of Solid Fuels by the Ignition-Point Method

Reactivity of various solid fuels was measured in the ignition-point apparatus. Minor improvements were made in the apparatus, but most of the work was directed toward determining the limitations of the method and its application to fuel-burning problems. If the entire sample of the coal was included, the rate of reaction at a given temperature was found to be proportional to the specific surface. With rejection of small sizes, this relationship may not hold. Study of the burning of fuels on open grates showed that the time required to reach the maximum burning rate or the quantity of fuel burned the first hour could be predicted from the ignition-point method. Factors other than external surface and reactivity, such as the porosity of the fuel, affected the burning rates of different types of fuels when burned under comparable conditions.

Stability and Structure of Burner Flames

The principles governing the attachment of flames to burner ports were studied. It was found that blow-off and flash-back limits of gas flow can

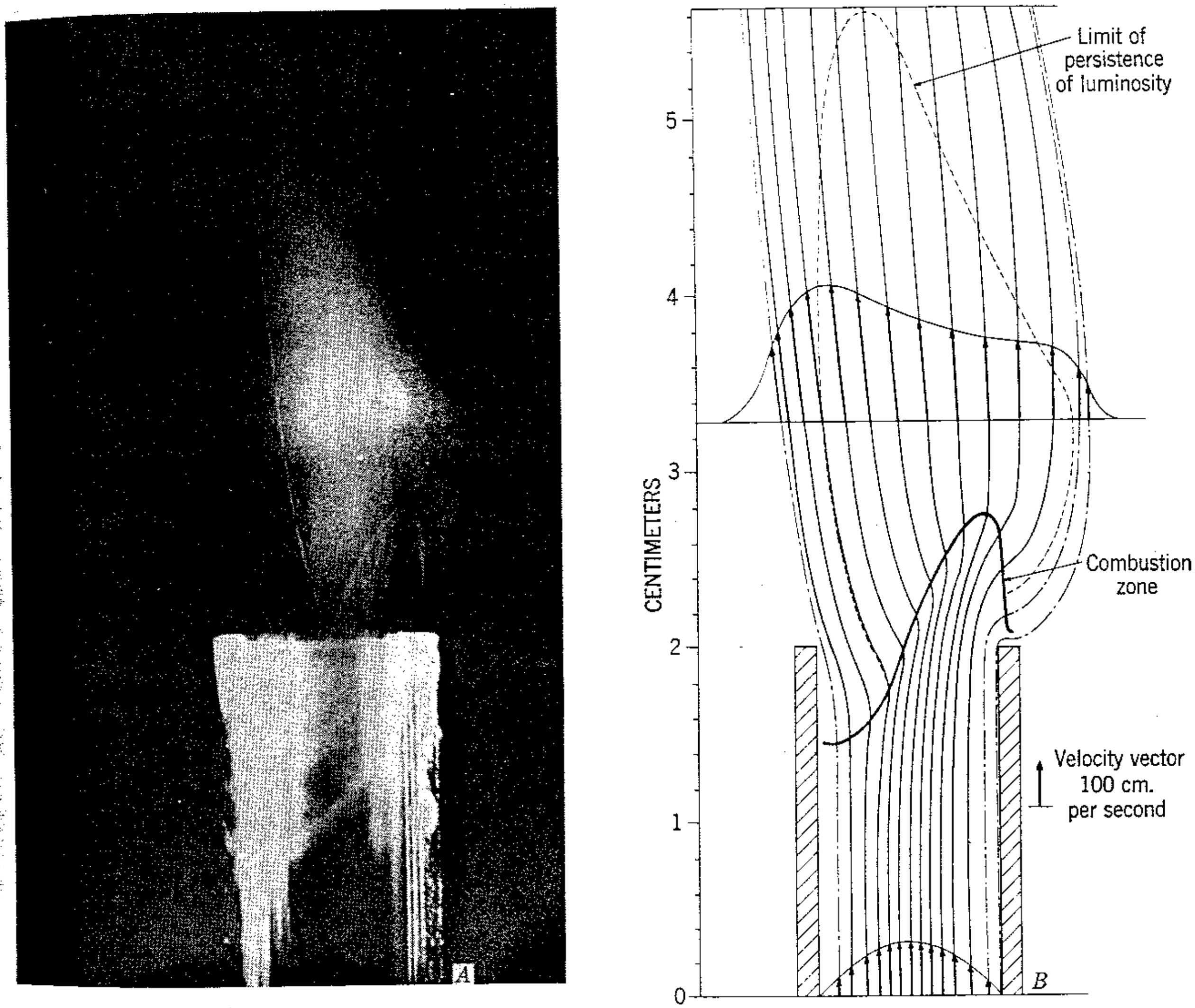

FIGURE 6.- Flame of natural gas and air, partly drawn into burner tube at gas flow just exceeding critical flow for flashback. Mixture composition, 8.1 percent natural gas in air; gas flow, 52 c.c. per second; inside diameter of tube, 1.068 cm. A, Photograph with particle tracks in vertical center plane (see Lewis and von Elbe, work cited). B, Diagram of flow pattern and velocity distribution. Solidly drawn flow lines are so located that the mass flow between any two adjoining lines is the same.