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RESEARCH MEMORANDUM

PRELIMINARY RESULTS OF A DETERMINATION OF TEMPERATURES OF FLAMES BY MEANS OF K-BAND MICROWAVE ATTENUATION

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The temperature effects on the attenuation of K-band microwaves at a frequency of 26,500±30 megacycles per second through natural-gas and propane flames containing added alkali halide salts were investigated over a temperature range from 1900° to 2500° K. The preliminary data of this investigation indicated that the attenuation varied appreciably with the sodium-line-reversal temperatures of the flames and was independent of the particular hydrocarbon fuels that were used for temperature sources and of the particular halide components of the compounds used, in the concentrations employed to produce easily measurable attenuation. A reproducibility of ±25° K was obtained.

INTRODUCTION

The measurement of high temperatures has become necessary in the evaluation of jet-engine and rocket performance. Of the temperature-measuring instruments available for low temperatures, few remain usable for temperatures above 1950° K, thereby introducing a need for instruments and techniques applicable in the high-temperature range.

The possibility of using microwave-radiation methods for high-temperature measurements was investigated at the NACA Lewis laboratory from October 1949 to December 1950. Theoretical considerations had indicated an expected shift in the frequency of microwaves traversing high-temperature mediums containing free electrons, but during the subsequent investigations for the predicted shift, none was uncovered. The large reductions in signal accompanying the passage of microwaves through flames, however, suggested the possibility of determining temperatures by attenuation measurements.

The attenuation measurement may be made by considering that the form of the electric field E (reference 1) of the microwave radiation is

$$E = E_0 e^{-i(\omega t - Kx)} \qquad (1)$$

where

E_0 initial electric vector

ω 2π multiplied by frequency of radiation

t time

K complex propagation constant of form $K = K_r + iK_i$; where K_i represents amplitude attenuation and K_r represents spatial phase angle

x distance traversed

The ratio of powers before and after traversing a slab of an attenuating medium, P_1 and P_2, respectively, is therefore

$$\frac{P_1}{P_2} = e^{2K_i x}$$

Hence, in units convenient for measurement,

$$K_i = \frac{0.115\left[10 \log (P_1/P_2)\right]}{x} \qquad (2)$$

where the quantity in the brackets is decibels of attenuation. In this report, x is measured in centimeters. If K_i, representing the attenuation the microwaves experience traversing a medium, is related to the temperature of that medium, the relation should be determinable by microwave-attenuation measurements on flames at various temperatures. By use, then, of some method for detecting power levels, a value P_1 may be determined for the condition where no attenuating medium is in the path of the microwave radiation; again, an attenuating medium placed in the radiation path will effect a new power level P_2.

A simplified analysis indicates that the free electrons of the medium are the greatest source of attenuation. The natural-gas and propane flames used to produce the attenuation were not sufficiently rich in free electrons to provide easily measurable values of attenuation; low-ionization-potential salts were therefore added to the flames to increase the free-electron concentration.

The preliminary data obtained for verifying the dependence of the attenuation of K-band microwaves upon the temperature of the medium are presented herein.

SYMBOLS

The following symbols are used in this report:

E	electric field of microwave radiation
E_0	initial electric vector
I	direct current
K	complex propagation constant of form $K = K_r + iK_i$
K_i	defined by equation (2)
K_r	defined in symbol list following equation (1)
P_1	unattenuated microwave power through medium
P_2	attenuated microwave power through medium
R	resistance
T	temperature, $^{\circ}K$
t	time
W_i	mass-flow rate of i^{th} alkali, grams per second
x	distance traversed
ω	2π multiplied by frequency of radiation

Subscript:

mw	microwave

APPARATUS AND PROCEDURE

It is reasonable to assume that the microwave-attenuation effects will be greatest for those frequencies reasonably close to the free-electron collision frequencies found in flames. For this reason, the K-band frequencies within the band from 23,000 to 27,000 megacycles per second were employed. A block diagram of the microwave apparatus is given in figure 1. Further information on microwave equipment may be found in reference 2 and the references given therein.

Microwave Apparatus and Attenuation Measurement Procedure

An Oxford-type 2K-33 klystron (fig. 1) with input voltages from the suitably regulated power supply 1 was used to generate the K-band microwaves. The output at approximately 26,500 megacycles per second was carried through brass waveguide and the various components to horn 1. Tuning of the transmitting line by varying the effective path lengths in the electric-vector and the magnetic-vector planes was achieved by using tuner 1; all tuning was accomplished for maximum signal to the receiver. Sufficient attenuation, approximately 12 decibels, was used to pad the klystron from any impedance changes in the line, particularly those that might have arisen from the flame under observation. This attenuation was provided by uncalibrated resistance-card, flap-type attenuator 1 giving a maximum of 25-decibels attenuation. The voltage-standing-wave-ratio, hereinafter designated VSWR, of the line was checked as a precaution by the VSWR detector to determine the flame effects on the VSWR. The detector, utilizing a traveling probe to absorb energy from the line, indicated no change in the amplitude or in the phase of the standing-wave pattern because of the flame. A transmission-type, resonant invar-cavity frequency meter was used to monitor the frequency of the microwaves. The average frequency, which was found to vary approximately 30 megacycles per second, was 26,500 megacycles per second. The energy was radiated into free space through long-transition-type horn 1. Both transmitting and receiving antennas (horns 1 and 2) were of gold-plated brass and of 25-centimeter length. At the operating ends of both, the dimensions were 5 centimeters by 14 centimeters. The horns apparently gave satisfactorily a beam of energy that could be entirely sent through the flames used. No radiation diagrams for the horns were obtained; however, from tests in which a number of conducting and nonconducting obstructing objects were placed in the beam, it was concluded that the beam was effectively 3 to 4 centimeters wide at the position of the flame.

The flame was normally located midway between horns 1 and 2, the separation between which was maintained at 50 centimeters. Attenuator 2, providing a maximum attenuation of 40 decibels, was used as a microwave shutter either to present full microwave power to the detector or to remove entirely the measurable microwave power. This attenuator was of the metallized mica-strip type; attenuation was accomplished by immersing the mica strip into the waveguide through a linkage connected to a rotor. Tuner 2 was identical in design and in use with tuner 1 of the transmitting line. A bolometer housed in a mount and having a tunable choke-type short-circuit to provide maximum transfer of energy to the bolometer was used for a detector. The bolometer used was of the Wollaston-wire type, the resistance of which changes, presumably independently of the frequency, with influx of microwave power. Tests indicated that the bolometer resistance was unaltered by radiation from the flame itself.

With a constant bolometer resistance, maintained because the VSWR in the line can vary with changes in the bolometer resistance, direct-current power and microwave power were simultaneously mixed, the measure of the removed direct-current power becoming a measure of added microwave power. The bolometer bridge used for this power-substitution method is shown in figure 2. The resistances R_b, R_2, R_3, and R_4 form the arms of a Wheatstone bridge, where R_b is the bolometer located within the waveguide.

For the measurements, the galvanometer G was of the taut-suspension, lamp-and-scale type, providing 1-millimeter scale deflection for 0.01-percent change in the bolometer resistance. Bolometer current was computed from the readings of the milliammeter A; the stated accuracy of the meter was 0.5 percent of full-scale reading. The experimentally determined reproducibility of the meter was 0.1 percent of full-scale reading. The Wheatstone bridge used was of the commercial type, having arms R_2 and R_4 in a ratio of 1:10. Bridge current was supplied by a 6-volt dry battery and regulated by means of a rheostat in series with a decade box to make up resistance R_5, as shown in figure 2. The bolometers were nominally operated at 100 to 150 ohms; several were used during this investigation.

The bridge is initially balanced with only direct-current power supplied to the bolometer. At this balance point, the power through the bolometer (resistance R_b) is

$$P_{b,1} = I_1^2 R_b \tag{3}$$

where I_1 is the direct current through the bolometer at balance 1. Microwave power is then allowed to fall on the bolometer by removing the attenuation in the line, thus causing a change in the resistance of the bolometer and unbalancing the bridge. When the bridge is rebalanced, the power dissipated through the bolometer at the second balance is

$$P_{b,2} = I_2^2 R_b + P_{mw} \tag{4}$$

where

I_2 direct current through bolometer at balance 2

P_{mw} unknown microwave power incident upon bolometer

But the resistance is unchanged for the two balances so that the powers are equal; hence

$$P_{mw} = R_b (I_1^2 - I_2^2) = P_1 \tag{5}$$

where P_1 now represents the full microwave power level. If attenuation of the microwave signal occurs by insertion of a flame, a new power level P_2 may be measured by the bolometer, leading to

$$\frac{P_1}{P_2} = \frac{I_1^2 - I_2^2}{I_1^2 - I_3^2} \tag{6}$$

where I_3 is the bolometer current after interposition of the flame.

The power ratio P_1/P_2 is therefore independent of the actual value of the bolometer resistance, provided that the resistance has not drifted during the three steps of measurement. With the 2K-33 klystron, the unattenuated power at the bolometer was approximately 0.2 milliwatts. During these observations, the flames used demonstrated no attenuation until salts having low-ionization potentials were added to them; hence a value of P_1 could be determined without removing the flame from the radiation path. Addition of the salts to the flame reduced the transmitted power; the attenuated value P_2 was then determined. Measurements accomplished by varying the position of the bolometer and of the tuners in the waveguide indicated that the phase of the microwaves was effectively unchanged by the flame or by the addition of salts to the flame. For this reason, consideration of the K_r portion of the propagation constant was not made.

The accuracy of the attenuation values obtained is limited largely by the accuracy of the milliammeter of the bolometer bridge; equation (6) is thus suitable for probable-error computations. An estimate of the probable error $\Delta(\mathrm{db})$ in the attenuation values is found by the usual methods to be

$$\Delta(\mathrm{db}) = 3.2\times10^{-5}\left[\frac{i_1^2(i_2^2 - i_3^2)^2 + i_2^2(i_3^2 - i_1^2)^2 + i_3^2(i_2^2 - i_1^2)^2}{(i_3^2 - i_1^2)^2\,(i_2^2 - i_1^2)^2}\right]^{1/2} \tag{7}$$

Application of this equation indicates that the attenuation measurements were good to approximately 0.05 decibels over the temperature range employed.

The microwave field about the flame was examined with a model TSK-3RL spectrum analyzer to investigate the intensity of scattered radiation.

Sodium-Line Apparatus

A block diagram of the sodium-line temperature apparatus is also shown in figure 1. Sodium-line-reversal temperatures were made using the standard technique (reference 3). The entire flame was so colored that an integrated temperature would be obtained for comparison with an integrated attenuation value. An alternating-current ammeter of 0.5-percent accuracy was used to read the current through a tungsten-strip projection lamp used as a comparison radiator. The calibration curve (temperature as a function of current) for the lamp was obtained with a portable, hand-balancing optical pyrometer of the disappearing-filament type. The absolute accuracy of this calibration, about $\pm 20^\circ$ K, is of less importance to this investigation than the ability to reproduce settings of the reversal point and the stability of the projection lamp. The reproducibility is estimated as $\pm 10^\circ$ K.

In order to obviate any effects of the solvent on the temperature evaluations when liquid solutions were employed for the attenuation data, the line-reversal temperatures were obtained when the sodium salts, requisite for the determination of the reversal points, and the solutions were simultaneously added to the flame. Dry sodium bromide powder was consistently used as the salt for the line-reversal measurements. The spectrometer used to determine the reversal point of the spectral lines was sufficiently good to resolve the sodium doublet readily.

Flame Apparatus

Flame burners were of the commercially available universal blast-lamp type, wherein fuel, air, and oxygen are used. Natural gas and propane gas were used alternately within the same burners. Since the flames were from 50 to 75 centimeters in length, it was easily possible to select a portion of the flame well above the inner cone. All observations were made through this portion of the flame located approximately 20 centimeters from the base of the flame. The average flame diameter of this selected portion was 4.5 centimeters. The flame diameters were sufficiently large to insure total passage of the cone of microwave radiation through the flame.

The low-ionization salts necessary for the attenuation and the line-reversal measurements were injected with nebulizers that gave a particularly fine spray which was rapidly diffused throughout the flame. The same nebulizer was used consistently for the attenuation data. Powder blowers were used for the line-reversal data as a convenience after it had been established that there was no significant difference in temperatures measured by injection of sodium solution and by injection of sodium powder.

The actual orientation employed, wherein the path of microwave travel is at right angles to the line-reversal path, is illustrated in figure 1.

In order to compare the attenuation measurements for various flame diameters and for ease in interpreting the data, the form "decibel loss per centimeter of flame path" is desirable. Any measurement of the "flame width" as a means of determining the flame path for attenuation is difficult. It is conceivable that this width varies with the quantity of salt added to the flame and perhaps also with the particular type of salt. In reality, what is desired is the effective free-electron width of the flame, or the path for attenuation. Approximations to this value may be obtained either with photographs or with wires heated in the flame (reference 4), neither of which appears to guarantee a satisfactory measure of the electron flame width. The device shown in figure 3 appears more closely to approach the type of flame-width measurement desired. Two pairs of wire probes, one pair on either side of the flame, are driven by direct-current motors toward the flame. When the resistance of the flame path between the probes of a particular pair drops below 20 megohms, the shut-off resistance of the electronic relay, the probe travel is halted. Thus, when both probes have been stopped by the free-electron conduction of the flame, the separation of the two pairs of probes is then a measure of the flame thickness. For these observations the separation was read directly from a scale mounted on the base of the probe carriers. Keys A and B and reversing switch S are provided to return the probes to their initial positions. The same salt concentration used to provide attenuation values was used to determine the flame widths in order to minimize the discrepancies due to salt concentrations within the flame. Repeated width measurements on the same flames indicated a reproducibility of 0.1 centimeter.

Experimental Procedure

The technique employed to determine the empirical relation between the attenuation and the temperature of the sources was as follows: The flame was initially adjusted by varying the fuel-air ratio to give a selected temperature. Two readings of this temperature, as determined by the sodium-line-reversal technique, were made immediately before and two further readings were made immediately after four successive evaluations of the microwave attenuation at that particular temperature. Following these measurements, four values were determined for the flame width using the apparatus shown in figure 2. About 5 minutes were required to perform all measurements at one temperature setting. Oxygen was added to the flame to increase the temperature levels above those obtainable with air.

The rate of salt addition was determined by weighing the quantity of salt before and after a run and dividing by the duration of the run. For each salt, attenuation was measured at approximately eight temperatures between 1900° and 2500° K; no attempt was made to repeat temperature values for the various salts investigated.

Attention was restricted to the bromides, chlorides, and iodides of cesium, potassium, rubidium, and sodium, for which the ionization potentials of both alkalis and halides are well known. Typical rates were 0.5 milligram of sodium iodide solution per second, 1.3 milligram of cesium iodide solution per second, and 0.06 to 0.10 milligram per second for the potassium-salt solutions.

Of the many gases available, natural gas and propane gas were chosen. Commercial propane was approximately 97 percent pure. Natural gas contained from 72- to 93-percent methane and from 5- to 20-percent ethane. The propane flame was much superior to the natural-gas flame with respect to stability and lack of alkali coloration.

DISCUSSION OF RESULTS

The typical results obtained for the alkalis used are illustrated in figures 4 and 5. Figure 4 illustrates, for a typical run, the variation of the attenuation with temperature.

The ordinate of figure 5 is expressed in power loss per unit path length per unit alkali-input rate in order to permit comparisons between halides, regardless of differences in alkali concentration. This type of expression involves the assumption that the attenuation by a salt is proportional to the salt concentration. No measurements were made of the volume-flow rates of the gases during this investigation. Because the flame heights were maintained sensibly constant, because gas, air, and oxygen pressures and flows were maintained fixed, and because the operating technique was standardized throughout the investigation, it is believed that the volume-flow rates were held within 5-percent for all alkali compounds at a given temperature of the flame.

The curves through the points of figure 5 were drawn with slight favor being shown toward the data obtained for the propane flames. The average deviation of any point from the curve is 25°; the average deviation of any propane-flame point is 20°. There appears to be no significant difference among the halides of any of the alkalis. These results are somewhat contrary to those of reference 4, wherein a difference of approximately 20 percent is reported for the absorption of the chloride and the iodide at a microwave frequency of 10,000 megacycles per second. The curves of figure 5 are replotted in figure 6 and reveal the dependence of the attenuation upon the alkali portion of the salt compounds.

The approximate sensitivities $d(K_i/W)/dT$, where W is the mass rate of alkali flow in grams per second and T is the Kelvin temperature, for the four alkalis are given in the following table at two temperatures:

Alkali	$d(K_i/W)/dT$	
	Temperature, °K	
	2050	2300
Sodium	0.31	0.70
Potassium	1.05	2.13
Rubidium	1.05	2.67
Cesium	1.74	1.84

The data values, in the form K_i centimeters^{-1} per W_i grams of alkali per second, used in the figures in this report were found to have an average probable error of 20 seconds per gram-centimeter for an error in the attenuation values of 0.05 decibel.

On the basis of the observed variations in the alternating-current line voltage, in the optical-pyrometer calibration of the lamp, in the estimates of the reversal points, and in the flame temperatures, it is doubtful whether the reproducibility of the sodium-line-reversal temperatures is closer than ±2 percent of the temperature at a given temperature. The spread of the data of figures 4 and 5 would indicate that the reproducibility is between ±1 to ±2 percent of the Kelvin temperature over the range from 1900° to 2500°.

Although the experiments offer no conclusive proof that the measured attenuations were caused by an absorption process, the results of traversing the microwave field about the flame with a spectrum analyzer suggested that absorption, rather than reflection or scattering, was the preponderant source of attenuation.

SUMMARY OF RESULTS

Empirical data were obtained relating the loss in microwave power through an attenuating medium with the sodium-line-reversal temperature of the medium. The feasibility has been thus demonstrated for the measurement of flame temperatures using microwave techniques. The attenuations obtained for salt input rates of the order of 10^{-5} grams per second were sufficient to provide temperature indications to a reproducibility of ±25° K of the sodium-line-reversal temperatures with the equipment used in this investigation.

Over a temperature range from 1900° to 2500° K, the attenuation of microwaves was found to be independent of the particular hydrocarbon fuels used to provide attenuating mediums and of the particular halide components of the salt compounds used to provide attenuation.

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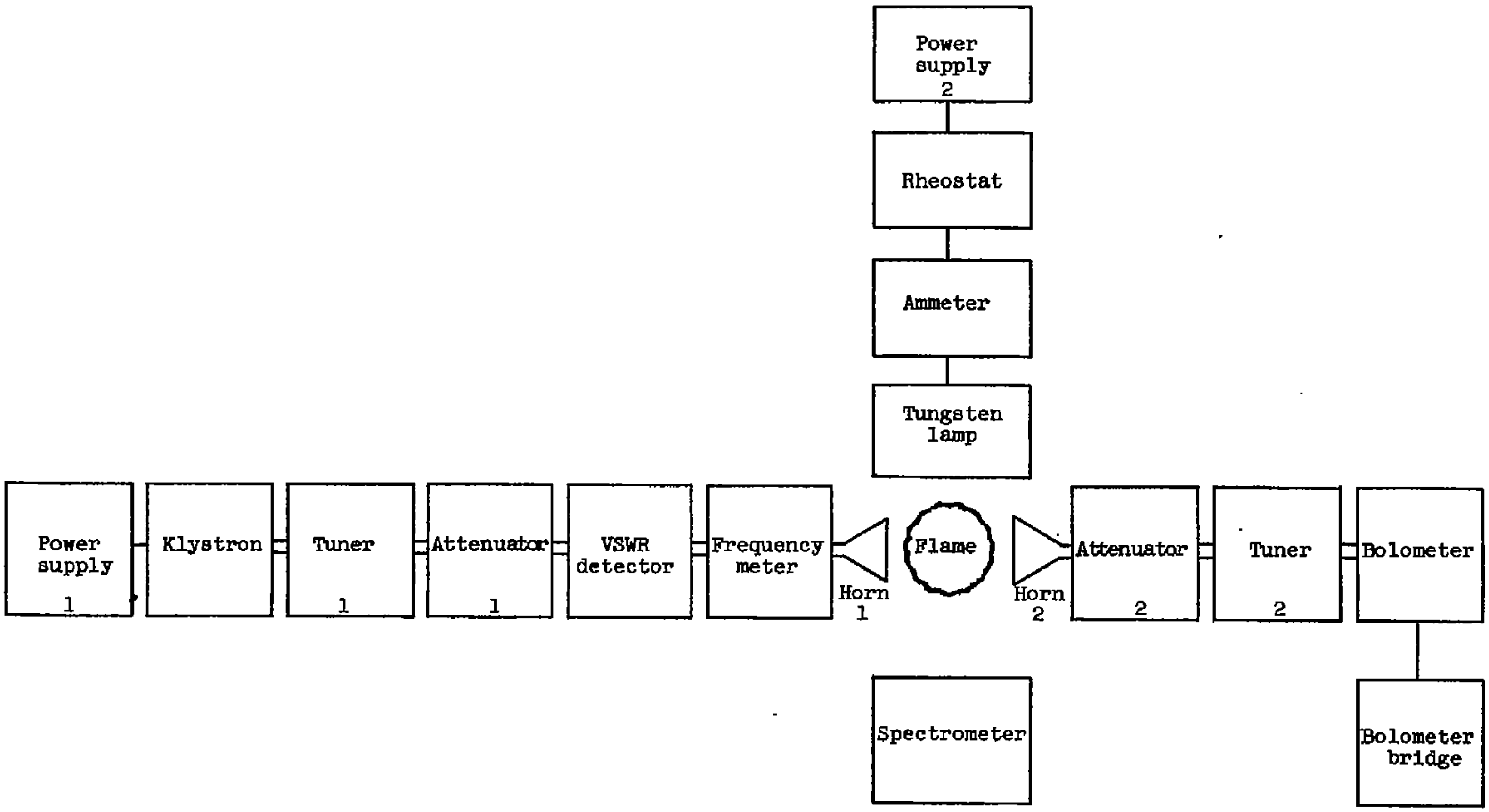

Figure 1. - Block diagram of attenuation and line-reversal apparatus.

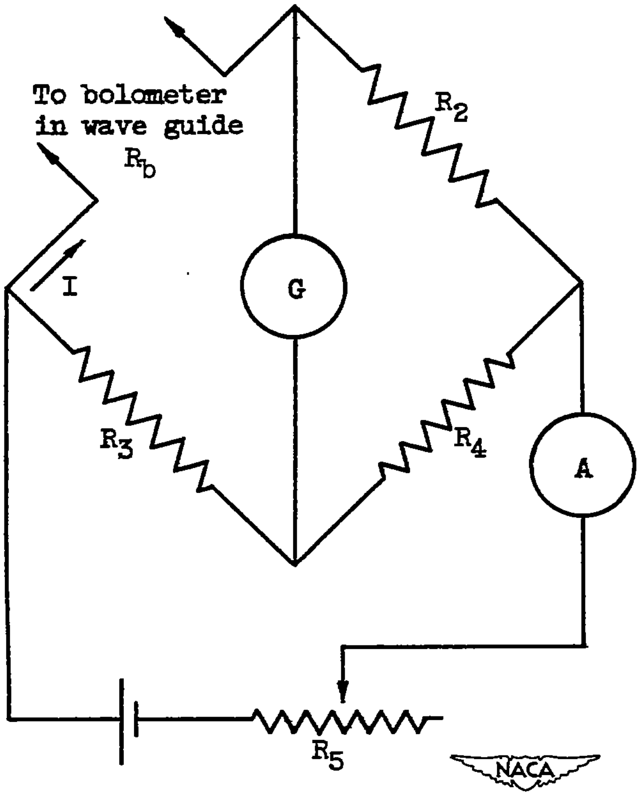

Figure 2. - Bolometer bridge.

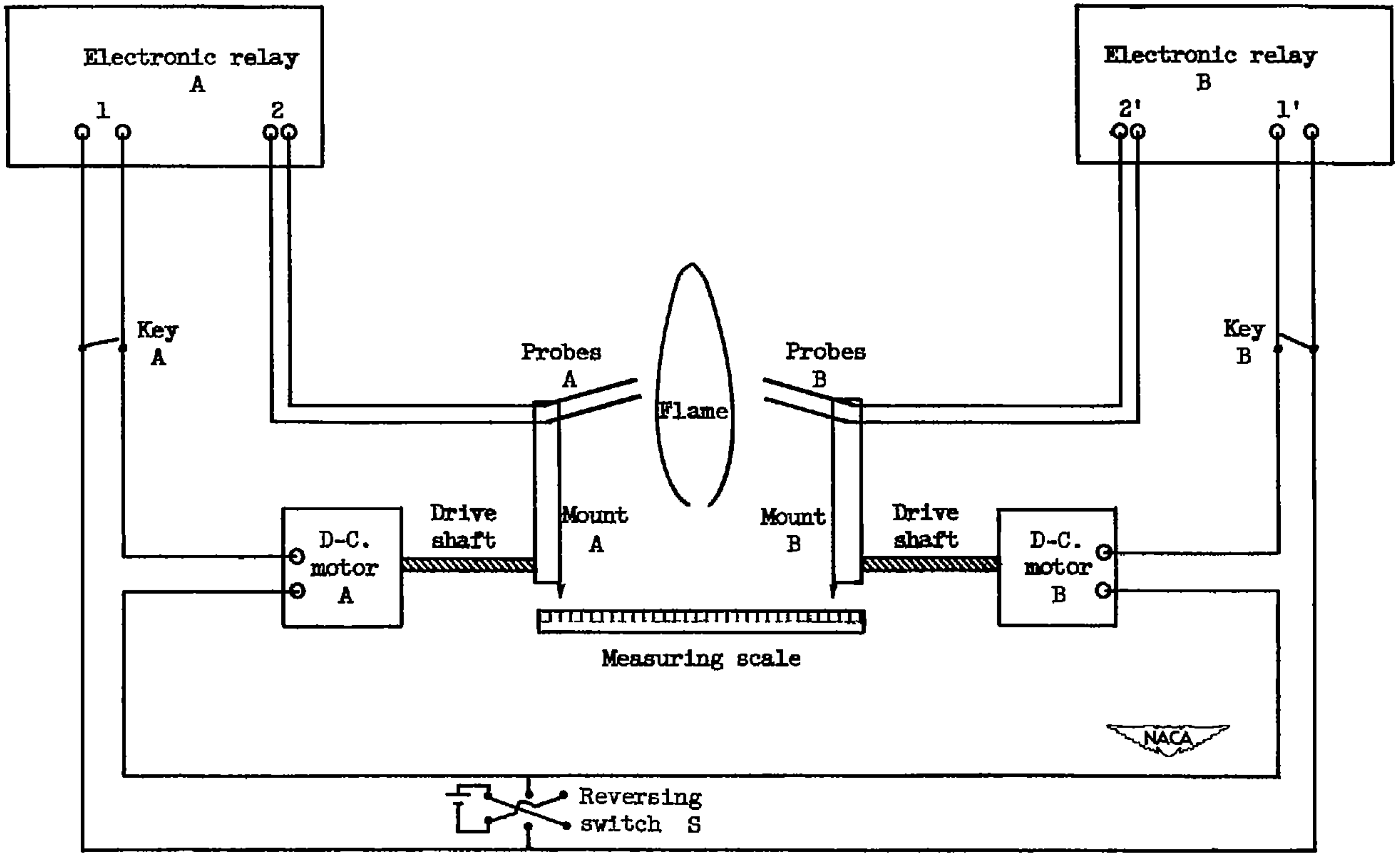

Figure 3. - Flame-width measuring apparatus (not to scale).

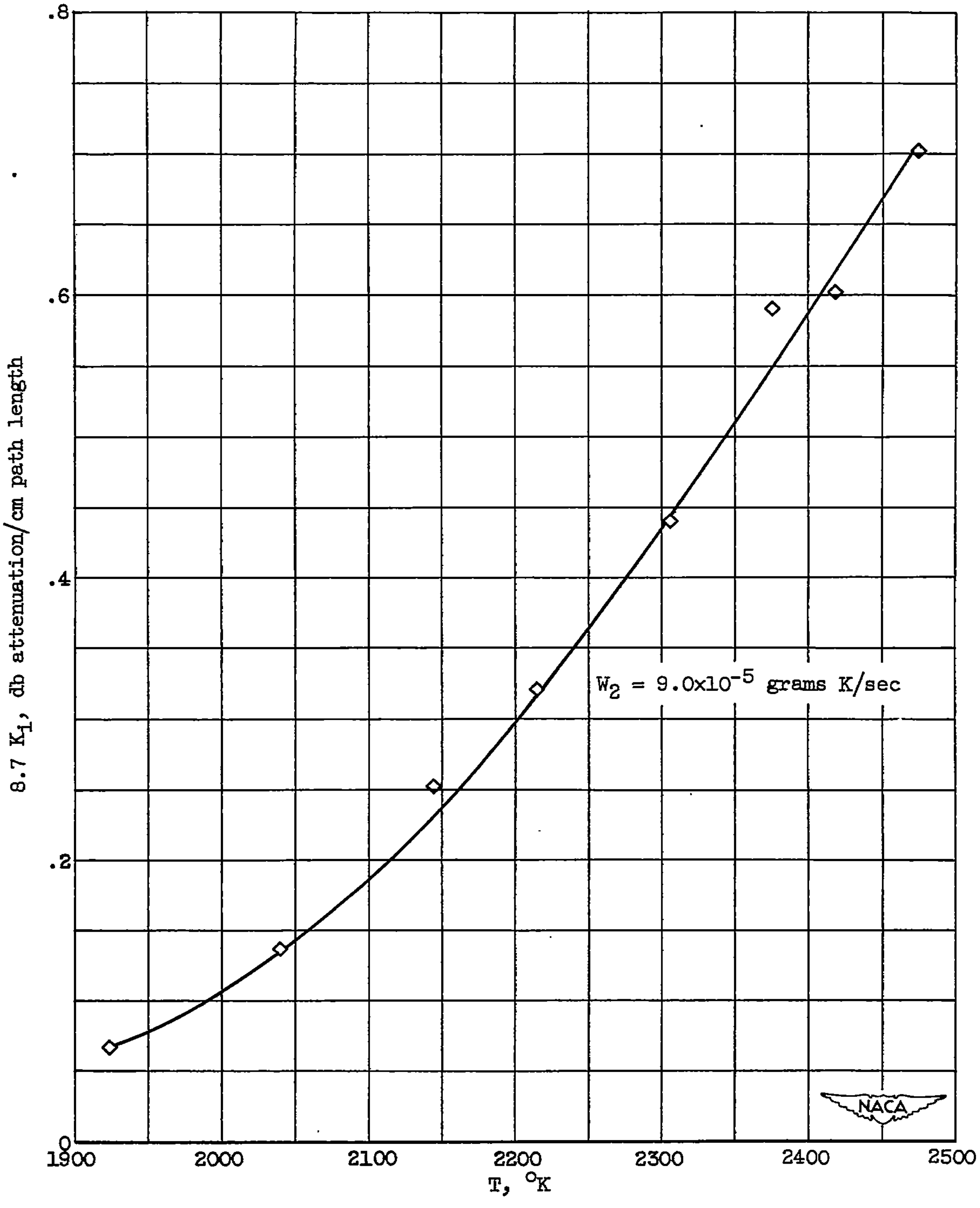

Figure 4. - Microwave attenuation by potassium iodide salt in propane flame.

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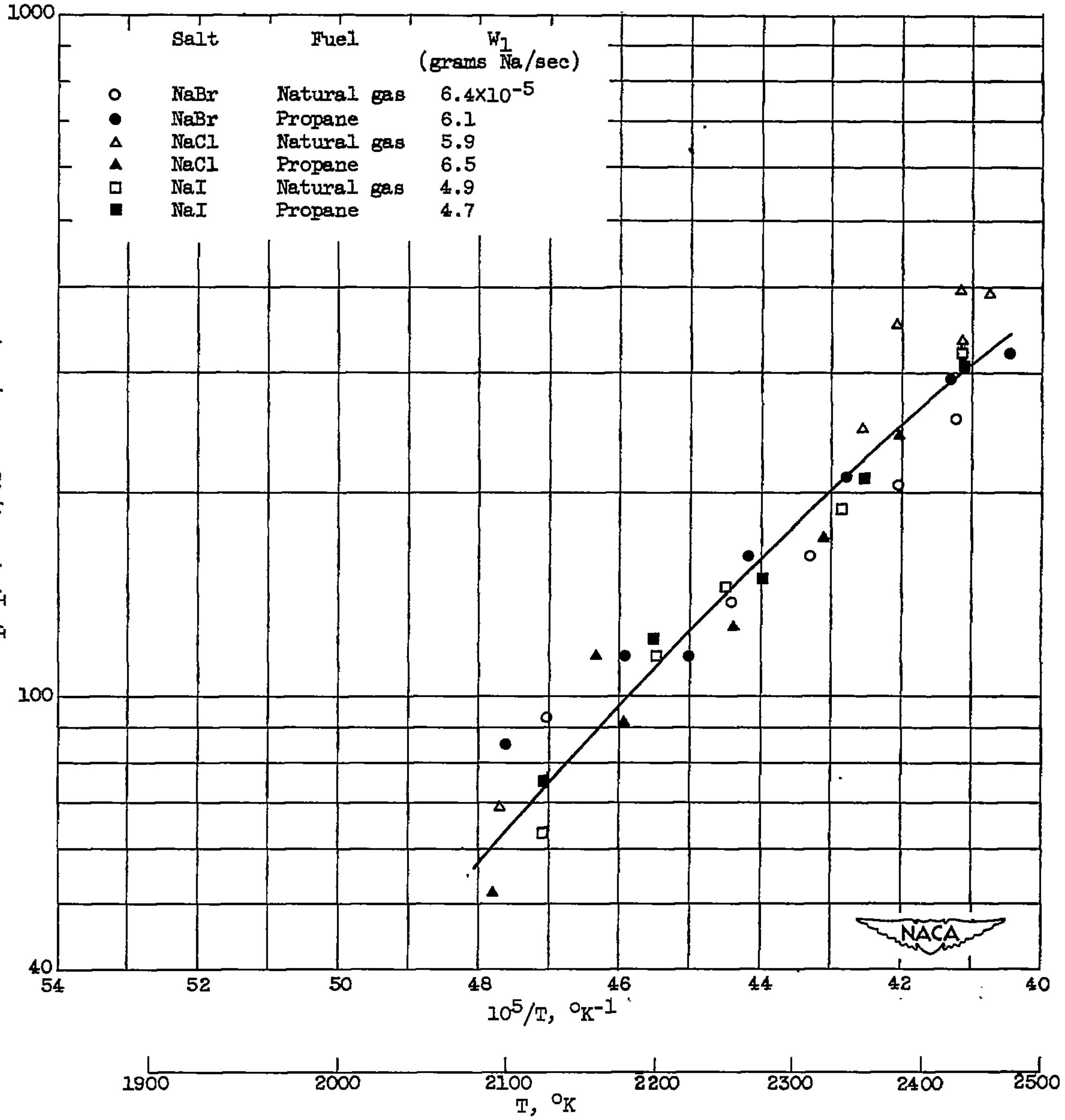
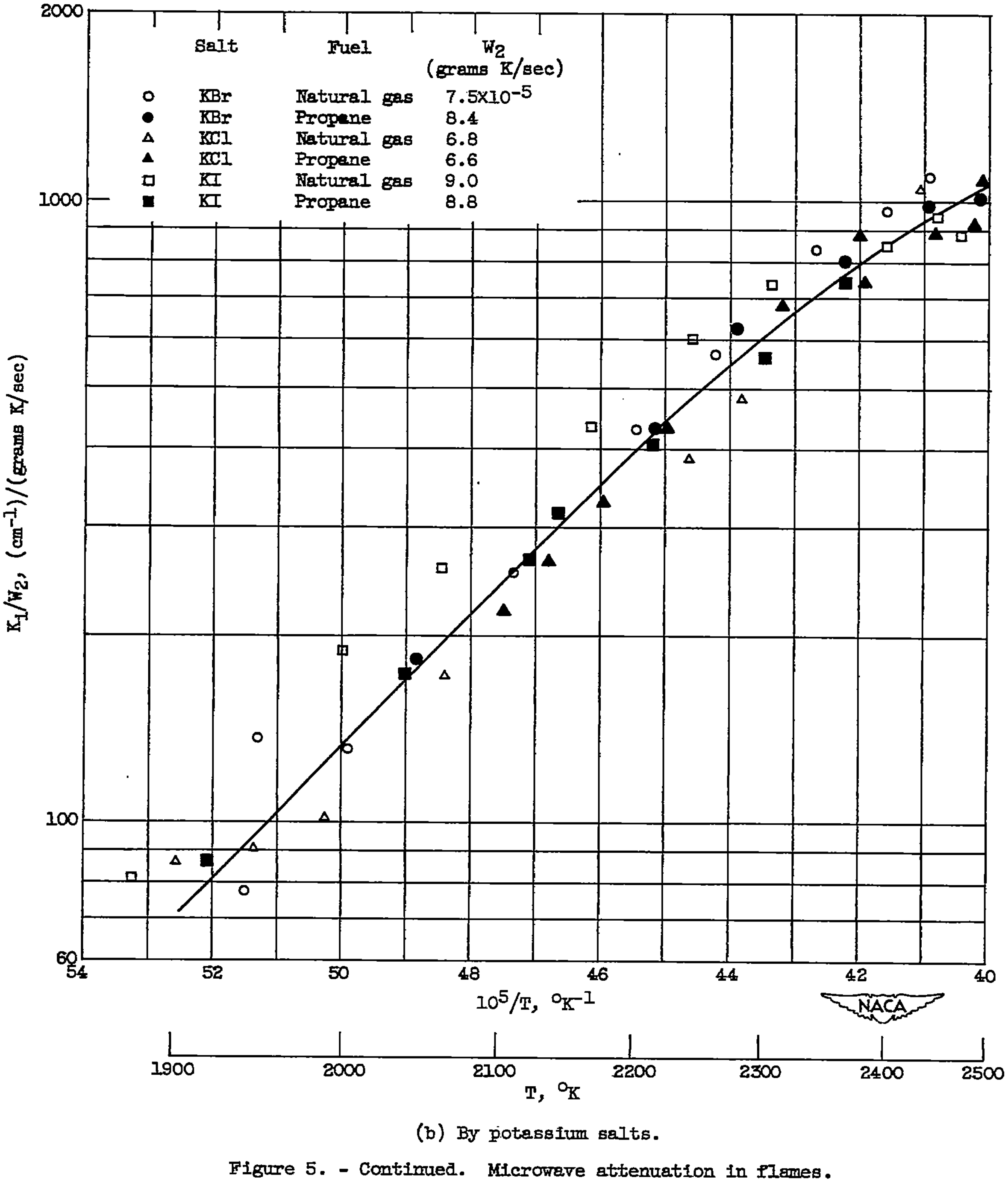


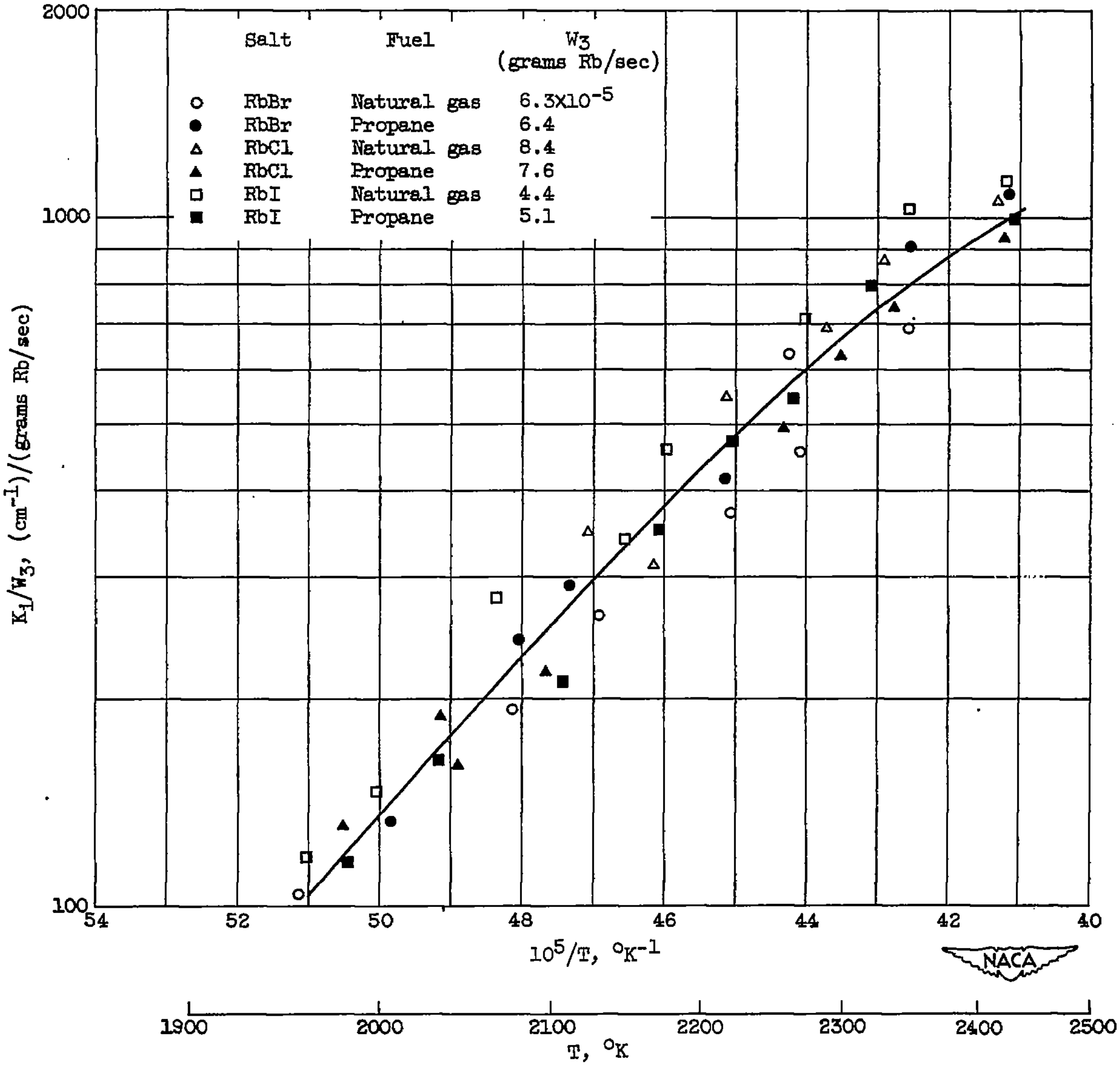
(a) By sodium salts.

Figure 5. - Microwave attenuation in flames.



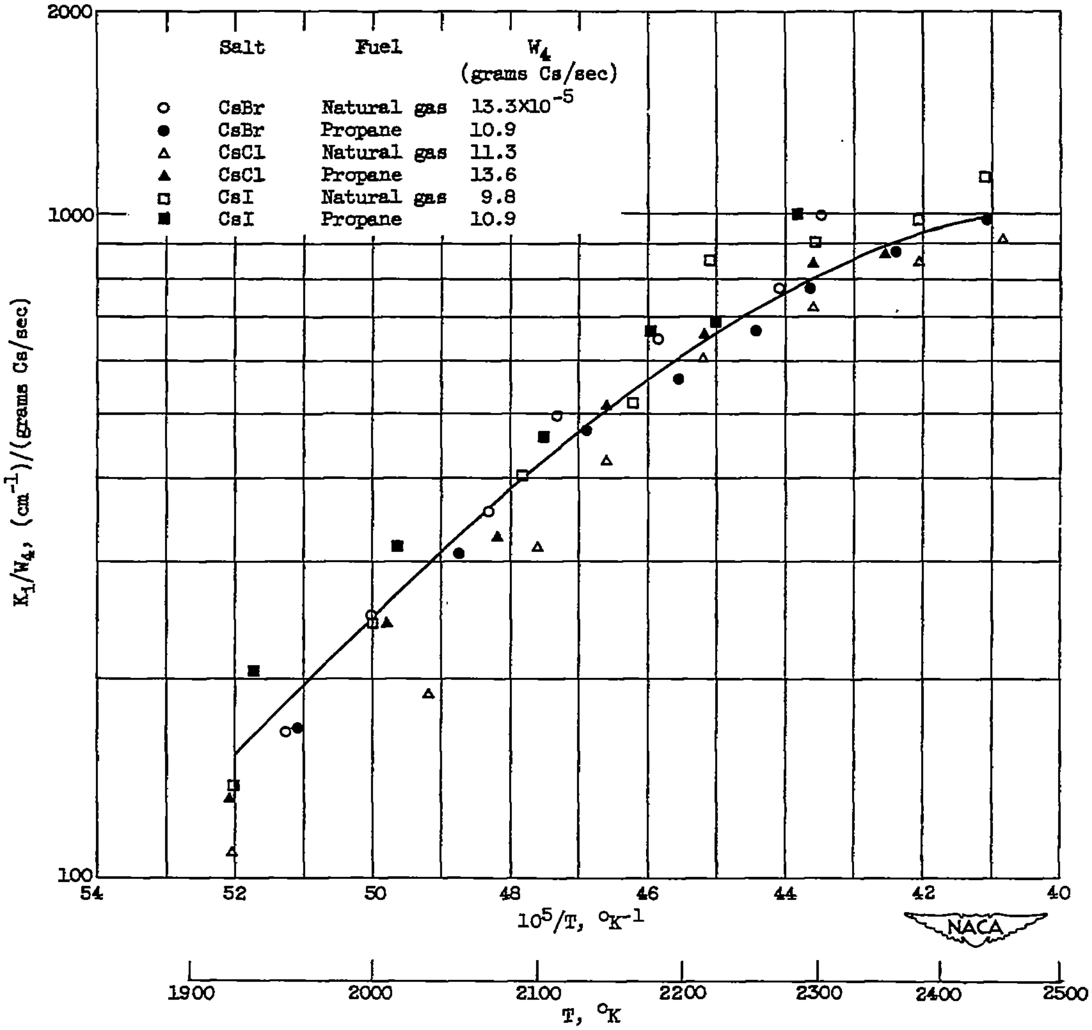
(b) By potassium salts.

Figure 5. - Continued. Microwave attenuation in flames.



(c) By rubidium salts.

Figure 5. - Continued. Microwave attenuation in flames.



(d) By cesium salts.

Figure 5. - Concluded. Microwave attenuation in flames.

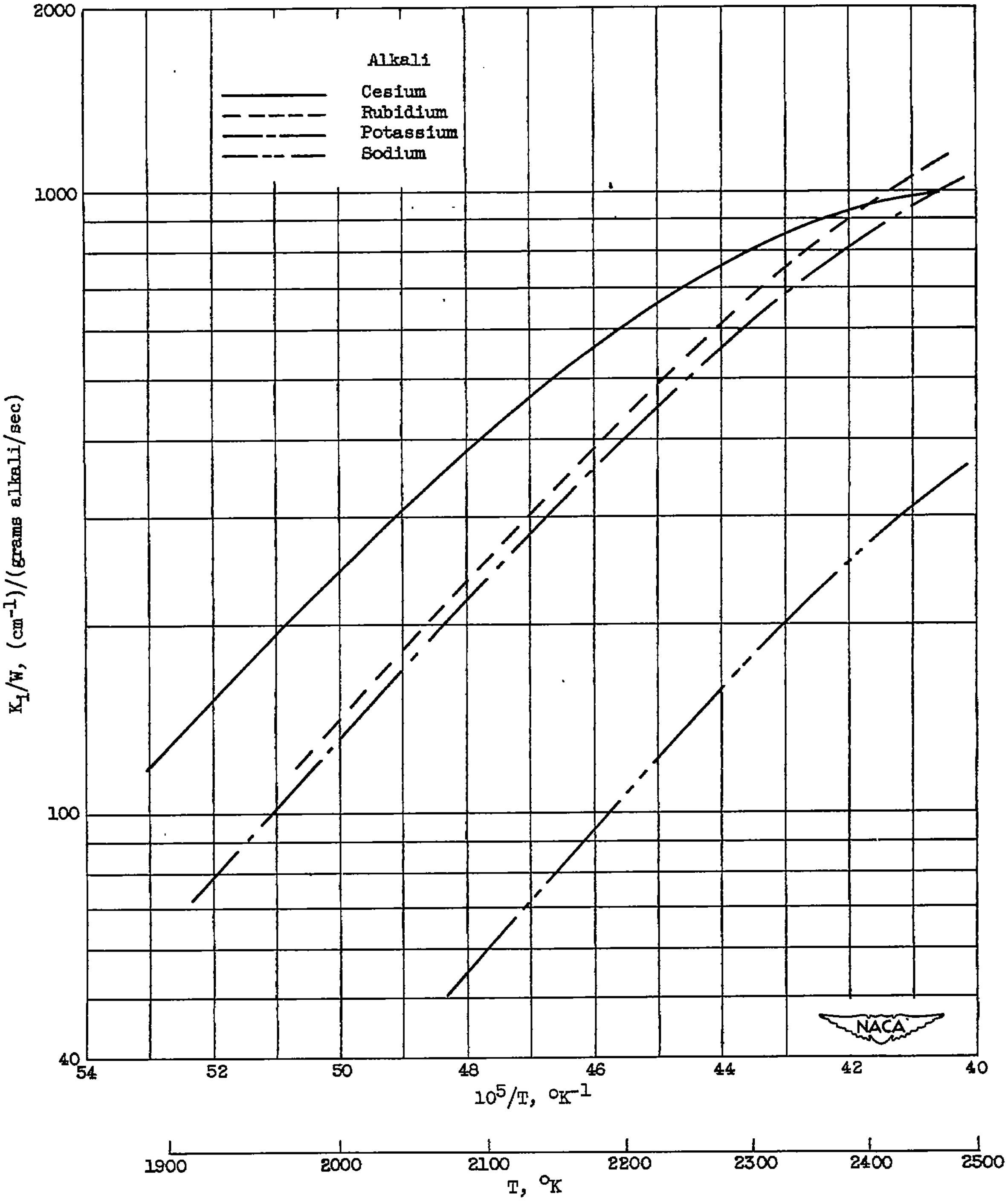


Figure 6. - Comparison of attenuations produced by four alkali salts.