substrate from above and the other on the film from below. Calibration was accomplished by adjusting the power input to the lamps until a thermocouple on the substrate indicated the Curie temperature at the same time a thick nickel film was at the Curie point. Measurements of the variation of Curie temperature with film thickness have also been made.

ACKNOWLEDGMENTS

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Microwave Discharge Cavities Operating at 2450 MHz

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Five simple microwave cavities for producing discharges in gases were tested in He and H_2 at pressures from 1 μ to 1 atm. Three of the cavities are commonly used, and two have been recently designed. One of the newly designed cavities offered a considerable improvement over early models with respect to compactness, ease of attachment to the system, and efficiency.

INTRODUCTION

During the past several years the microwave discharge has found increasing application as an excitation source for gaseous electronics studies, for light sources, and for the production of free radicals. This discharge source has many attractive characteristics: (1) It produces a high degree of ionization and a large amount of molecular dissociation without undue heating of the background gas; (2) with no need for internal electrodes, it is possible to construct reaction vessels which are simpler, freer from contamination, and less subject to damage; (3) it produces little electrical interference; and (4) the source presents no dangerous high voltage which can be easily contacted.

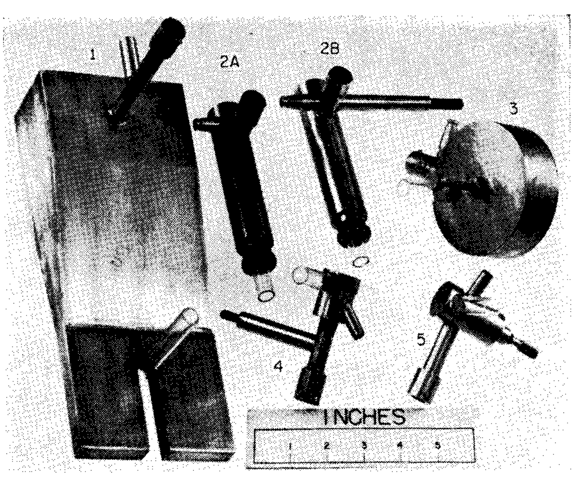

Fig. 1. This photograph shows the relative sizes of the various cavities. The 13-mm-o.d. Pyrex tubing occupying the position of the discharge source adds perspective to the picture.

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Many early sources were fashioned from government surplus radar equipment but, usually, considerable knowledge of microwave techniques was required to procure and assemble an adequate system. The need for an inexpensive, uncomplicated source of cw microwave power was finally satisfied to a great extent through the use of medical diathermy units which supply a maximum of about 125 W at 2450 MHz.

The usefulness of this power source rests on the proper choice of discharge cavities. It is the purpose of this paper to describe three established and two relatively new cavity

Table I. Cavity characteristics.

Cavity	Electrical configuration	Estimated frequency range (MHz)	Coupling adjustment	Removable from glass discharge system
1	Tapered rectangular TE_{013}	2.45	Yes	Yes
2a	Foreshortened $\frac{3}{4}$ wave coaxial	2.3–2.6	No	No
2b	Foreshortened $\frac{3}{4}$ coaxial	2.3–2.6	Yes	No
3	Foreshortened $\frac{1}{4}$ wave radial	2.3–2.6	No	No
4	Coaxial termination	0.5–4.5	Yes	Yes
5	Foreshortened $\frac{1}{4}$ wave coaxial	2.0–3.0	Yes	Yes

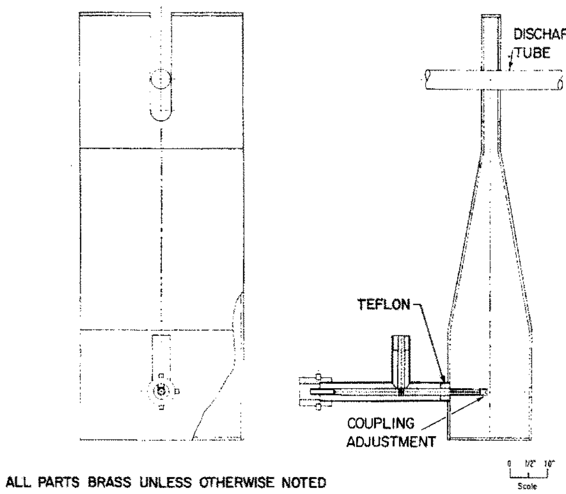

FIG. 2. A simple drawing of cavity 1.

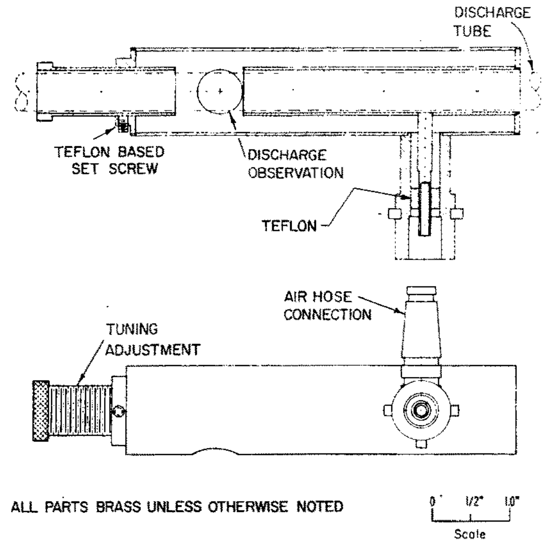

FIG. 3. A simple drawning of cavity 2A.

designs and to compare their operation in various gases at different pressures.

The purpose of the discharge cavity is to transfer power from the microwave source to the gas, which is contained in a glass tube. A resonant structure (cavity) is used to increase the electric field in the gas. To match the impedance of this structure to that of the coaxial line of the microwave power supply some sort of coupling device is used. When the resonant frequency of this structure is tuned to that of the diathermy unit and the impedance is matched, then the power reflected from the cavity is a minimum. This minimum value varies with different cavities. An increase in the efficiency of the cavities is indicated by a decrease in the reflected power. The presence of a discharge in the resonator changes the resonant frequency and also changes the loaded Q factor. The properties of the discharge change with pressure and with different gases; it is therefore necessary to provide both tuning and matching adjustments to obtain efficient operation over a wide range of discharge conditions. These facts were not always realized in the development of some of these cavities, which resulted in the poor performance noted in these tests.

THE CAVITIES

The five basic cavities which were tested are shown in 2A, designated 2B, the cavities are arranged in chronological order with respect to their development. The object of all modifications was to produce an effective, compact discharge source. The progress toward the latter objective can be seen in Fig. 1. Cutaway drawings of each of the cavities are shown in Figs. 2–7. The cavities will be discussed individually in order of their listing in Fig. 1.

Some of the basic features of the cavities are listed in Table I. (Designations of the cavities were obtained from Ramo and Whinnery.[1]) Table I gives the microwave configuration of the cavities, the frequency ranges, and coupling adjustments; and indicates whether the cavity may be removed from the discharge tube without breaking the vacuum system.

All of these cavities were designed to produce discharges in a tube 13 mm o.d., since this size glassware has been found to be convenient. However, the cavities may be modified to accommodate larger or smaller discharge tubes. In each cavity the glassware is located in a region of strong electric field.

Cavity 1 (Fig. 2) was one of the earliest microwave excitation sources used in this laboratory.[2] The slot cut in the narrow portion of the cavity provides the useful feature that the cavity may be placed in position and removed without breaking the gas-handling system. Best operating conditions usually are obtained when the discharge tube is placed midway along the slot near the edge (not as shown in Fig. 1). A screw in the coupling probe permits adjustment of the probe depth to achieve best coupling.

Cavity number 2A (Fig. 3) has been in use several years.[3–6] In this cavity the discharge is struck in the gap between the hollow inner cylinders through which the discharge tube eccentrically slips (see Figs. 1 and 3). The tuning of the cavity is accomplished by the gap distance between the varying inner cylinders. In order to obtain a good, uniform electrical connection between the outer conductor and the variable inner conductor, a Teflon-tipped

[1] S. Ramo and J. R. Whinnery, *Fields and Waves in Modern Radio* (John Wiley & Sons, Inc., New York, 1953), p. 438.
[2] H. P. Broida and M. W. Chapman, Anal. Chem. **30**, 2049 (1950).
[3] M. Zellikoff, P. H. Wykoff, L. M. Aschenbrand, and R. S. Loomis, J. Opt. Soc. Am. **42**, 818 (1952).
[4] L. Bovey, Spectrochim. Acta **10**, 432 (1958).
[5] H. E. Radford, Phys. Rev. **126**, 1035 (1962).
[6] E. F. Worden, R. G. Gutmacher, and J. G. Conway, Appl. Opt. **2**, 707 (1963).

set screw has been added. Moreover, setting this screw prevents detuning the cavity by accidental movement of the variable inner conductor. The hose fitting on the coaxial connector allows cooling air to be blown through the cavity to prevent overheating of the discharge tube. The hole in the outer cylinder of the cavity permits the observation of light from the discharge region. It might be mentioned that the hole in the inner conductor of this cavity is a waveguide beyond cutoff at 2450 MHz. Since the plasma is generally confined to the gap region, this cavity effectively contains the microwave radiation.

Cavity 2B (Fig. 4) is identical to 2A except for the addition of an adjustable matching stub which is located on the coaxial connector opposite the hose fitting (see Figs. 1 and 4). In 2B the tuning is accomplished by the simultaneous adjustment of the matching stub and variation of the gap distance. Cavity 3 (Fig. 5) is a foreshortened radial line loaded by the capacitance of the $\frac{1}{4}$-28 tuning screw.[1,7] As in 2A, a Teflon-tipped set screw was provided to obtain reproducible, uniform tuning and locking. Positioning of the off-axis hole was arrived at by a trial and error method to give the most intense discharge. Tight magnetic field coupling between line and cavity is achieved by the large inductive loops. An air hose connection is placed on the coaxial connector to provide cooling for the discharge tube.

Cavity number 4 (Fig. 6) was recently developed. Change in coupling is accomplished by means of a matching stub located on the coaxial connector. Additional changes in the coupling can be effected by adjustment of the shaped probe. A piece of 9.5-mm brass tubing is located on the body of the discharge source to allow cooling air to be directed on the discharge tube. The removable cap permits the unit to be positioned without breaking the vacuum system. It should be noted that this cavity is not a resonant cavity in the sense of the other discharge cavities. While the other cavities were designed to operate at 2450 MHz and perform only over a limited band about this frequency, cavity 4 has worked well over a band width greater than 1000 MHz.

Cavity 5 (Fig. 7) is also of recent development. The resonant frequency of this cavity is adjusted by means of the tuning stub and the coupling by means of an adjustable coupling slider. The wide operating range achieved by this cavity is due to the presence of both adjustments. In tuning the cavity with the discharge in operation, the tuning stub is adjusted for a minimum reflected power with the minimum probe penetration. Next, the probe is adjusted. Since these two operations are not independent, successive readjustment will improve the efficiency. With a 13-mm discharge tube, optimum tuning is obtained with the end tuning stub about 5 mm from the discharge tube and the metal end of the coupling slider located about halfway be-

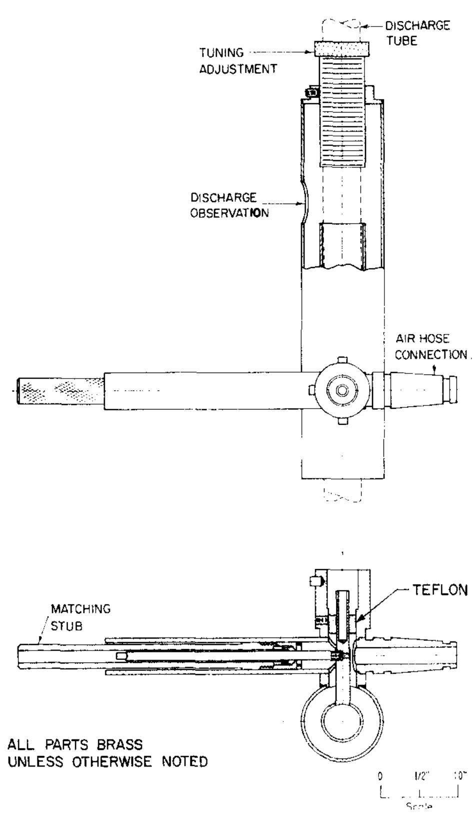

FIG. 4. A simple drawing of cavity 2B.

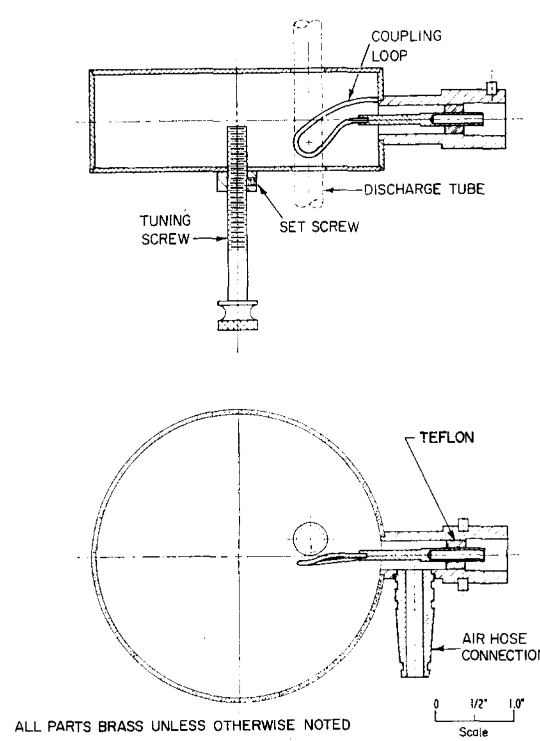

FIG. 5. A simple drawing of cavity 3.

[7] A. L. Schmeltekopf and H. P. Broida, J. Chem. Phys. 39, 1216 (1963).

tween the end of the coaxial line and the tuning stub. In adjusting the coupling probe, two minima may occur in the reflected power. The one corresponding to maximum coupler penetration is associated with arcing between the tuning stub and the coupling probe and should be avoided. Cooling air is directed on the discharge through the tube located in the body of the source. The removable cap allows the unit to be positioned without breaking the vacuum system.

This cavity possesses one design feature which may require slight modification of the microwave power generator. To simplify construction, this cavity does not have a positive dc short from the inner coaxial cable to the outer conducting shield. Most medical diathermy units require this short before power is supplied to the magnetron. This is to prevent the magnetron from working into an open line which would reflect a large amount of power into the magnetron and shorten its life. To bypass this feature, the anode of the magnetron may be directly shorted to ground around the relay. To prevent damage to the magnetron the microwave power supply should be turned off before one disconnects the cavity.

OPERATING CHARACTERISTICS

In order to provide information on which of these discharge cavities is most effective the following measurements are reported in Table II: (1) the pressure range between 1 μ and 1 atm in hydrogen and helium over which the discharge can be maintained; and (2) the percent of power reflected from the discharge cavity operating at pressures of 0.1, 1, 10, and 100 mm Hg. In the pressure range measurements, the pressure of helium or hydrogen was allowed to slowly increase or decrease until the discharge was quenched. Since operating conditions change

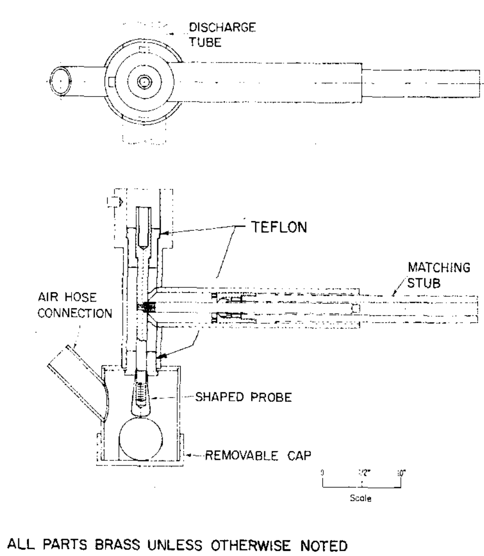

FIG. 6. A simple drawing of cavity 4.

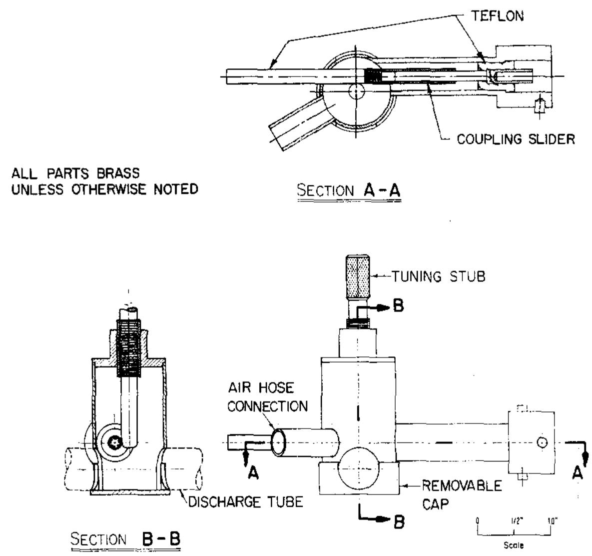

FIG. 7. A simple drawing of cavity 5.

with variations in pressure, the cavity tuning was readjusted to maintain a minimum in the power reflected from the cavity. Since the percent of reflected power over this pressure range was similar for air, N_2, O_2, H_2, Ar, and He, only the results for He are given in Table II. The reflected, as well as the incident power, was measured using a bi-directional power meter located at the output of the microwave power generator. Usually minimizing the reflected power produced the strongest discharge for a given input power. Full microwave power was used in both tests.

The measurements were made in slowly flowing gases (1 to 20 atm cc/sec in 13 -mm-o.d. quartz tubing). Pressures above 1 mm Hg were measured with an aneroid manometer, while pressures below 1 mm Hg were measured with a heat conductivity gauge. It should be noted that these measurements were made using reagent grade cylinder gases. In situations where high gas purity is maintained or in which different glass tubing is used, the pressure range over which the cavities operate may be greatly changed. Accordingly, the results which are quoted should be considered indicative only. Although in all of the cavities the discharge may start spontaneously, it may be

TABLE II. Operating characteristics.

Cavity	Pressure range (mm Hg) over which discharge source operates. He		H_2		Percent reflected power in He.			
	Low	High	Low	High	0.1	1	10	100 mm Hg
1	0.07	600	0.04	28	78	28	4	15
2a	0.01	>700	0.03	240	50	30	18	10
2b	0.01	>700	0.02	400	46	5	4	4
3	<0.001	>700	0.01	210	22	56	63	55
4	<0.001	>700	0.01	250	<1	33	44	30
5	<0.001	>700	<0.001	>450	<1	<1	<1	<1

initiated over a wider range of pressures with the aid of a Tesla coil.

In the pressure range measurements, only the results for helium and hydrogen are given in Table II. However, similar measurements were made in oxygen, nitrogen, and air. In the latter gases the discharge could be maintained in all cavities except cavity 1 to very high pressures. "Hot spots" in the discharge tube appeared at pressures of about 400 mm in hydrogen and oxygen and 600 mm in nitrogen. The presence of the "hot spots" was indicated by the appearance of the sodium yellow doublet in the emission spectrum of the discharge. Additional air cooling of the discharge vessel did not prevent this heating which could rather quickly melt the glassware. Heating was not observed in the rare gases, indicating that this effect was probably due to wall recombination.

Cavity 1 was found to be useful over a limited range of pressures in comparison with other cavities. This cavity was found to operate between 0.003 and 48 mm Hg in nitrogen, and between 0.002 and 82 mm Hg in oxygen. In both these gases, the other cavities maintained a discharge from less than 0.001 mm Hg to the pressure at which "hot spots" developed. In addition, even in the rare gases, large amounts of power were reflected because of an inadequacy of the tuning adjustments. Due to its cumbersome size and its relatively poor performance, cavity 1 is now seldom used in our laboratory.

Cavity 2A may be operated over a much wider range of pressures than 1. It gives satisfactory performance with oxygen, nitrogen, and hydrogen, operating at high pressures. This cavity operates most efficiently when the gas pressure is above 1 mm Hg. In cavity 2B the addition of the matching stub to this cavity considerably enhances its efficiency and extends the range of operation. This cavity is not as convenient to use as 4 and 5, nor as efficient as 5.

Cavity 3 operates over as great a range of pressures in the various gases as 2B. Cavity 3 operates most efficiently at low pressures. The measurements indicate the operation of 3 in the low pressure region to be somewhat better than 2B, while the reverse is true in the high pressure region. At higher pressures, the discharge is confined to a region close to the wall of the discharge tube nearest the coupling loop. In this region, heating of the glassware again was observed at high pressures. This cavity is about as convenient in use as 2B.

Cavity 4 operates over a range of pressures as great as cavities 2 and 3. This result is shown in Table II. The matching adjustment arrangement is adequate, however, only at low pressures as shown. While 4 is as convenient to use as 5, it is not as efficient over as wide a range of pressures.

Cavity 5 exhibits the widest pressure range for operation and is nearly 100% efficient over this entire range. The high pressure limitation of the operation of this cavity in H_2 was imposed by the fact that the cooling used could not prevent the quartz discharge vessel from melting. A strong discharge was produced by this cavity in low pressure hydrogen which was characterized by a spectrum consisting principally of emission from atomic hydrogen indicating its possible use as an atomic hydrogen light source.

In the preceding discussion five types of discharge cavities have been described. In each case the Q's of the cavities are relatively low (<1000). Their effectiveness arises from the fact that the cavity containing the discharge can be well matched to the microwave power source. In over-all ability to produce a discharge in a wide variety of conditions, cavity 5 has proved to be most effective. Cavity 5 also is more convenient to use than 1 through 3. In all cavities except 1, a discharge could be maintained over a pressure range from about 1 μ to near 1 atm for even such gases as N_2, O_2, and H_2. Cavities 3 and 4 performed somewhat better at pressures less than 1 mm Hg while cavity 2 gave better results at pressures above 10 mm Hg. The operation of cavity 5 was superior over the entire range of pressures. Thus cavity 5 offers a considerable improvement over earlier models in all important respects.

In general, the optimum tuning for initiation of breakdown does not correspond to the optimum tuning when the discharge is in operation. Careful tuning is advisable since, aside from the advantage derived from a strong, steady discharge, the deleterious effects of the reflected microwave power on connecting cables and the microwave power source is reduced. Optimum performance of all of the cavities is achieved only when good electrical contact is maintained in the various tuning adjustments and between the coaxial line and the cavity.

Fairly large amounts of microwave power may be radiated from these sources when the discharge is in operation. In fact, in all sources except 2A and 2B, a discharge may extend several centimeters in the tube outside the cavity. For applications in which stray radiation is objectionable or hazardous,[8,9] the addition of shielding sleeves along the discharge tube should prove worthwhile (household aluminum foil is quite satisfactory).

Many of the cavities described here have been used for several years by our colleagues, and we are very much indebted to them for their valuable comments, assistance, and suggestions.[10]

The support of the Advanced Research Projects Agency and the Defence Atomic Support Agency is gratefully acknowledged.

[8] A. F. Harvey, *Microwave Engineering* (Academic Press Inc., New York, 1963), p. 973.
[9] W. W. Mumford, Proc. IRE **49**, 427 (1961).
[10] Detailed working drawings of the cavities are available from the authors.