Rectangular and Ridge Waveguide*

TORE N. ANDERSON†

Summary—This paper describes the present state of the art with respect to rectangular ridge waveguide giving tables and data from standard waveguide sizes and constructional techniques for both rigid and flexible waveguide. The problems inherent in waveguide connectors are discussed along with the various methods for producing waveguide assemblies.

The problems inherent with present-day waveguide standardization are also discussed. It is essential that a series of standard waveguide for high pressure operation and for extremely broad-band operation (ridgeguide) be standardized.

The latest RETMA miniature standard flanges are shown along with present-day thinking on a series of pressurized contact flanges.

INTRODUCTION

SINCE THE title "Rectangular and Ridge Waveguide" is not technically correct according to the recently published IRE standards for waveguides, the proper definition is included here for clarification. This paper deals with the subject of "uni-conductor rectangular waveguides and ridged uni-conductor rectangular waveguides operating in the fundamental transverse electric (TE_{10}) mode" as defined by the IRE. However, by popular usage, "rectangular and ridged waveguide" are terms that will probably continue to be used for many years to come.

The field of rectangular waveguide is the one in which more work has been done from both the theoretical and practical point of view. Ridged waveguide has only begun to be important as a microwave transmission line for a number of specialized applications.

The history of rectangular waveguide, as far as we know, dates back only about 20 years for practical applications, although a number of early workers in electromagnetism discussed the possibility of propagating energy through hollow pipes. It was the work of G. E. Southworth, A. E. Bowen, A. P. King, A. J. Schelkunoff, and W. L. Barrow that resulted in practical use of rectangular waveguide. Despite the relative newness of the field, the basic mathematical relations describing waveguide propagation were set down by James Clerk Maxwell more than 83 years ago.

For a complete history of waveguides, the reader is referred to Dr. Southworth's book, "Principles and Applications of Waveguide Transmission." Dr. Southworth's historical description is probably the best written history of waveguides that can be found, and made all the more interesting since, as a graduate student at Yale, Southworth first noticed a peculiar behavior of electric waves propagated on a pair of wires in a trough of water. He went on later to investigate this phenomenon and this was the beginning of the practical application of waveguides.

* Manuscript received by the PGMTT, July 17, 1956. Invited paper presented before the Panel on Guided Microwave Transmissions at the IRE National Symposium on Microwave Techniques, Benjamin Franklin Center for Physical Sciences, University of Pennsylvania, Philadelphia, Pa., February 2, 1956.

† Airtron, Inc., Linden, N. J.

RECTANGULAR WAVEGUIDES

Theory of Operation

The theory of operation of rectangular waveguides has been covered in a number of published works and will not be repeated here. Instead, a short review of the results and their practical considerations will be given.

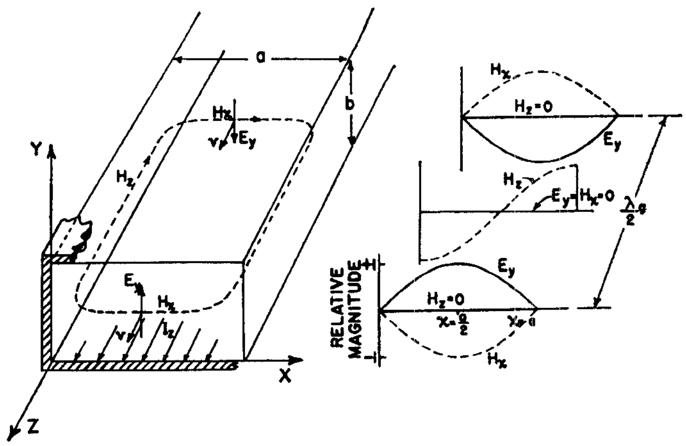


Fig. 1.

Fig. 1 shows in outline form the electric and magnetic fields which are present in a half-wavelength section of waveguide of dimensions a and b for the fundamental (TE_{10}) mode. The waveguide behaves as a high pass filter, with the cutoff wavelength and frequency given below:

$$\lambda c = 2a \text{ (for air dielectric waveguide)} \qquad (1a)$$

$$fc = \frac{C}{\lambda c} = \frac{3 \times 10^{10}}{2a} \qquad (1b)$$

where a and λc are in cm and fc is in cps.

For this mode of propagation, E_x, E_z, and H_y all equal zero. The electric field vector E_y reaches a maximum at the middle of the broad wall, which is an important point to keep in mind when designing waveguide components for operation at very high peak power levels. As there are no transverse currents flowing in the narrow walls of the waveguide, a vertical gap can exist without disturbing the field configuration. Conversely, there is no longitudinal component of current along the center line of the broad wall, thereby making it possible to slot the broad wall at this point without disturbing the fields.

As one goes higher in frequency, the first higher order mode is encountered, the TE_{20} mode, for which the following relations hold:

$$\lambda c_{20} = a \tag{2a}$$

$$fc_{20} = \frac{C}{\lambda c_{20}} = \frac{3 \times 10^{10}}{a}. \tag{2b}$$

It is between the TE_{10} and TE_{20} cutoff frequencies that most of the work in rectangular waveguide is done; however, in some extremely broad band applications, very broad or flat waveguide is used where the aspect ratio (a/b) is considerably larger than 2 to 1. In this case, operation may be in a frequency range which will allow the existence of the TE_{20} mode. This procedure is generally dangerous in that higher order mode resonances and mismatches may result, although techniques can be adopted to minimize these effects. However, as a general rule, it is advisable to operate only between the extremes of TE_{10} and TE_{20} cutoff.

The choice of dimensions for a waveguide involves several other considerations. The most important of these are attenuation and voltage breakdown. As TE_{10} cutoff is approached, the attenuation of a given waveguide increases quite rapidly, and the power handling capacity also decreases. Therefore, it is considered good practice to operate at frequencies no lower than 10 per cent above TE_{10} cutoff and up to a point of approximately 5 per cent below TE_{20} cutoff. Another consideration in choice of operating frequency for a given size waveguide is the rate of change of guide wavelength as a function of frequency. Guide wavelength for any mode is given by

$$\lambda g = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda c}\right)^2}} \tag{3}$$

where λ_0 = free space wavelength.

The attenuation of rectangular waveguide, neglecting dielectric losses, is given by

$$\alpha c = \frac{.00859}{a^{3/2}} \left[\frac{\frac{a}{2b}\left(\frac{2a}{\lambda_0}\right)^{3/2} + \left(\frac{2a}{\lambda_0}\right)^{-1/2}}{\sqrt{\left(\frac{2a}{\lambda_0}\right)^2 - 1}} \right] \text{db/meter.} \tag{4}$$

For minimum attenuation over the largest possible frequency range, the ratio of a/b should be exactly 2.0. Unfortunately, many of our standard waveguides were chosen from architectural tubing due to the wartime emergency, and therefore, these waveguides have aspect ratios which vary about the ideal figure of 2.0.

Table I is a tabulation of standard rectangular waveguide dimensions taken from the RETMA standard TR-108A. The numbering system employs the prefix WR (waveguide-rectangular) followed by a number giving the wide (a) dimension of the waveguide in one-hundredths of an inch. For example, WR-1500 measures 15.00 inches in the wide dimension. An original series of waveguide dimensions were chosen to meet the needs of the military in 1942, and these are now known as Series A, and remain military standard waveguides. To meet the needs for overlapping frequency ranges, a committee

TABLE I

DIMENSIONS, TOLERANCES, AND FREQUENCY RANGE FOR RIGID RECTANGULAR WAVEGUIDES

RMA+ Designation	Frequency Range (kmc/a) for Dominant (TE_{10}) Mode	Dimensions in Inches								Maximum Inner Radius
		Inner Dimensions			Outer Dimensions			Wall Thickness		
		A	B	Tolerance	C	D	Tolerance	Nominal	Deviation from Mean	
WR1500	0.47– 0.75	15.000	7.500	±0.015	15.250	7.750	±0.015	0.125	±0.015	3/64
WR1150	0.64– 0.96	11.500	5.750	±0.015	11.750	6.000	±0.015	0.125	±0.015	3/64
WR975	0.75– 1.12	9.750	4.875	±0.010	10.000	5.125	±0.010	0.125	±0.010	3/64
WR770	0.96– 1.45	7.700	3.850	±0.005	7.950	4.100	±0.005	0.125	±0.009	3/64
WR650	1.12– 1.70	6.500	3.250	±0.005	6.660	3.410	±0.005	0.080	±0.008	3/64
WR510	1.45– 2.20	5.100	2.550	±0.005	5.260	2.710	±0.005	0.080	±0.008	3/64
WR430	1.70– 2.60	4.300	2.150	±0.005	4.460	2.310	±0.005	0.080	±0.008	3/64
WR340	2.20– 3.30	3.400	1.700	±0.005	3.560	1.860	±0.005	0.080	±0.007	3/64
WR284	2.60– 3.95	2.840	1.340	±0.005	3.000	1.500	±0.005	0.080	±0.006	3/64
WR229	3.30– 4.90	2.290	1.145	±0.005	2.418	1.273	±0.005	0.064	±0.005	3/64
WR187	3.95– 5.85	1.872	0.872	±0.005	2.000	1.000	±0.005	0.064	±0.004	1/32
WR159	4.90– 7.05	1.590	0.795	±0.004	1.718	0.923	±0.004	0.064	±0.004	1/32
WR137	5.85 –8.20	1.372	0.622	±0.004	1.500	0.750	±0.004	0.064	±0.004	1/32
WR112	7.05– 10.00	1.122	0.497	±0.004	1.250	0.625	±0.004	0.064	±0.004	1/32
WR90	8.20–12.40	0.900	0.400	±0.003	1.000	0.500	±0.003	0.050	±0.004	1/32
WR75	10.00– 15.00	0.750	0.375	±0.003	0.850	0.475	±0.003	0.050	±0.004	1/32
WR62	12.4 –18.00	0.622	0.311	±0.003	0.702	0.391	±0.003	0.040	±0.003	1/64
WR51	15.00– 22.00	0.510	0.255	±0.0025	0.590	0.335	±0.003	0.040	±0.003	1/64
WR42	18.00–26.50	0.420	0.170	±0.0020	0.500	0.250	±0.003	0.040	±0.003	1/64
WR34	22.00– 33.00	0.340	0.170	±0.0020	0.420	0.250	±0.003	0.040	±0.003	1/64
WR28	26.50–40.00	0.280	0.140	±0.0015	0.360	0.220	±0.002	0.040	±0.002	1/64
WR22	33.00– 50.00	0.224	0.112	±0.0010	0.304	0.192	±0.002	0.040	±0.002	0.010
WR19	40.00–60.00	0.188	0.094	±0.0010	0.268	0.174	±0.002	0.040	±0.002	0.010
WR15	50.00– 75.00	0.148	0.074	±0.0010	0.228	0.154	±0.002	0.040	±0.002	0.008
WR12	60.00–90.00	0.122	0.061	±0.0005	0.202	0.141	±0.002	0.040	±0.002	0.006
WR10	75.00–110 00	0.100	0.050	±0.0005	0.180	0.130	±0.002	0.040	±0.002	0.006

on waveguides of the Radio Manufacturers Association (RMA), which is now active as the SQ-11.1 committee of the RETMA on waveguides and fittings, adopted a series known as Series B which provided an overlapping frequency range. The Series B waveguides can be identified from Table I by the right hand column of frequency ranges in the second column of the figure.

The power than can be handled by a rectangular waveguide operating in the TE_{10} mode is given by

$$P = 756ab\sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2} \text{ kilowatts.} \tag{5}$$

Mechanical Tolerances

Sudden changes in the internal dimensions of the waveguide, or differences in dimensions at the junction of two waveguides, may lead to objectionable reflections. These imperfections may be likened to sudden changes in characteristic impedance, and for the case of two similar waveguides with slightly different dimensions, the mismatch at the junction is given approximately by

$$r = \frac{Z_1}{Z_0} = \frac{a_0 b_1}{a_1 b_0} \text{ (neglecting frequency sensitive terms)} \tag{6}$$

where r = vswr, and a_1, b_1, a_0, b_0 = cross sectional dimensions of waveguides.

This equation, although not completely rigorous, is accurate enough for small mismatches and yields results sufficiently good for engineering purposes to establish practical tolerances. From this general consideration, it appears that satisfactory waveguide can be fabricated from sheet metal for the larger rectangular waveguide sizes. For the shorter wavelengths (12 cm to 1 cm), standard drawn seamless tubing is satisfactory for most applications. For wavelengths less than 1 cm, special techniques are required to obtain the necessary accuracy. Table I gives the standard tolerances which have been adopted by the RETMA. However, these tolerances are far from satisfactory for the most precise of applications, and are probably too loose for economical manufacture of precision waveguide components and assemblies. For these applications, special redrawn or broached waveguide tubing should be used. Tolerances held to a third of those specified in Table I are required for many applications and the engineers designing these components should carefully review the application for best results.

Materials

Since attentuation is not usually serious for the larger sizes of waveguide, the materials are dictated by mechanical considerations such as weight, rigidity, pressurization, etc. At the higher frequencies, however, attenuation may not be ignored and silver and copper waveguides are required. Since the attenuation losses are confined to an extremely thin layer of metal at microwave frequencies, laminated or bimetallic structures are fairly common. At the lowest waveguide frequency, neither corrosion nor minor variations in the surface of the waveguide structure appear to affect attenuation, but both are of importance at the higher frequencies. At frequencies above 9.0 kmc the attenuation is generally somewhat higher than calculated from direct current conductivity considerations. It is presumed that the differential is a result of surface imperfections in the waveguide. At the lower frequencies, thin films of low loss, low dielectric constant, dielectric materials are used occasionally as a protective finish without affecting attenuation seriously.

Constructional Techniques

In the larger waveguide sizes, WR-1500 to WR-975, sheet metal fabrication techniques are generally used with both copper-clad steel and aluminum waveguides finding popular acceptance. These are generally formed in two halves with a riveted or molded seam along the middle of the broad wall. In the middle range of waveguide sizes, WR-650 to WR-28, seamless rectangular waveguide tubes are obtained by metal drawing techniques. In the millimeter wavelength region, because of the extremely close tolerances that are required, sections are generally electroformed around hard steel mandrels which are subsequently removed. Fig. 2 illustrates the waveguide cross sections discussed.

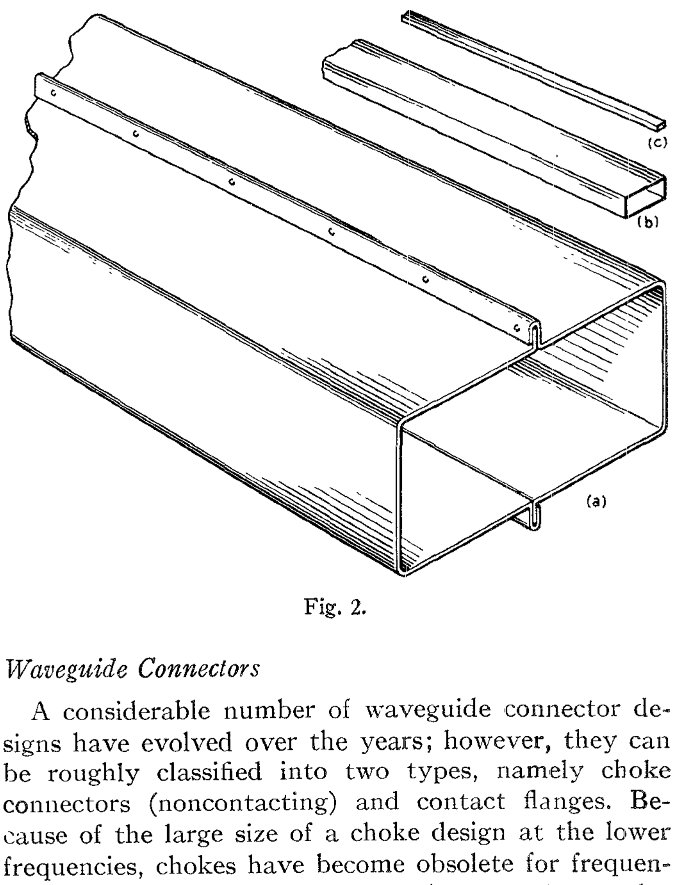


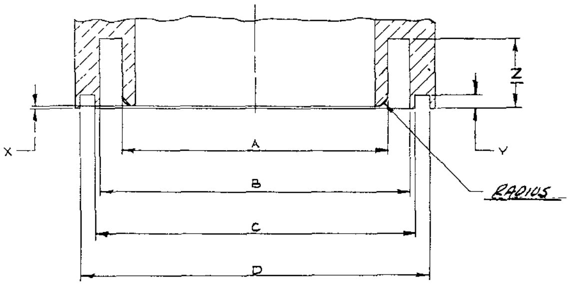
Fig. 2.

Waveguide Connectors

A considerable number of waveguide connector designs have evolved over the years; however, they can be roughly classified into two types, namely choke connectors (noncontacting) and contact flanges. Because of the large size of a choke design at the lower frequencies, chokes have become obsolete for frequencies below 2600 mc/sec. They are, however, in popular use for frequencies from 2600 mc/sec up to 40,000 mc/sec. The standard nominal dimensions for chokes covering this frequency range are shown in Table II.

TABLE II

NEW BROADBAND CHOKE DIMENSIONS AS PER APRIL, 1950



Size id	Size od	*A*	Tol.	*B*	Tol.	*C*	Tol.	*D*	Tol.
2.840×1.340	3.000×1.500	3.320	±0.005	3.880	±0.005	4.000	±0.005	4.450	±0.005
1.872×0.782	2.000×1.000	2.190	±0.003	2.556	±0.003	2.690	±0.005	2.949	±0.005
1.372×0.622	1.500×0.750	1.598	±0.003	1.860	±0.003	2.125	±0.003	2.429	±0.005
1.122×0.497	1.250×0.625	1.270	±0.003	1.495	±0.003	1.561	±0.003	1.765	±0.005
0.900×0.400	1.000×0.500	1.015	±0.002	1.225	±0.002	1.340	±0.003	1.540	±0.005
0.622×0.311	0.702×0.391	0.710	±0.002	0.828	±0.002	0.875	±0.003	1.195	±0.005

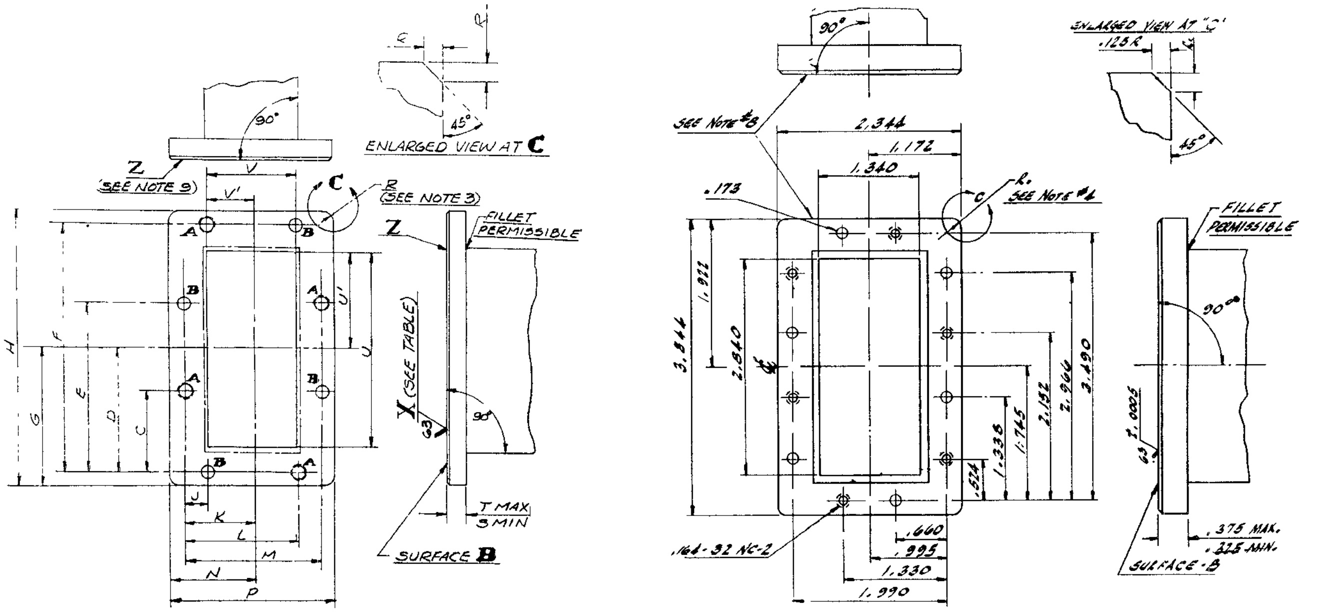
Size id	Size od	*X*	Tol.	*Y*	Tol.	*Z*	Tol.	Radius	Mates with Cover Flange	ANRFCCC Dwg. No.*
2.840×1.340	3.000×1.500	0.036	±0.001	0.165	±0.005	0.860	±0.005	0.090 R	UG-214/U	RE 49 F 334
1.872×1.782	3.000×1.000	0.025	±0.001	0.088	±0.003	0.570	±0.003	0.060 R	UG-149A/U	RE 49 F 279
1.372×0.622	1.500×0.750	0.017	±0.001 −0.000	0.108	±0.002	0.405	±0.003	0.040 R	UG-344/U	RE 49 F 456
1.122×0.497	1.250×0.625	0.015	±0.001	0.069	±0.002	0.345	±0.003	0.030 R	UG-51/U	RE 49 F 203
0.900×0.400	1.000×0.500	0.0115	+0.0010 −0.0000	0.073	±0.002	0.265	±0.003	0.020 R	UG-39/U	RE 49 F 197
0.622×0.311	0.702×0.391	0.0075	+0.0010 −0.0000	0.105	±0.002	0.190	±0.003	0.016 R	UG-419/U	RE 49 F 497

* For cover flange.

Choke-cover flange combinations have the advantage of being relatively simple to assemble, but since the flange faces do not make contact at the waveguide itself, mismatch contributions as large as 1.02 may be introduced by their use. At the present time, standard military drawings on choke-cover flange combinations suffer from several defects: 1) the dimensioning and tolerances allowed are not entirely correct; 2) the O-ring gasket groove is not properly designed, which is evidenced by a large number of O-ring failures. At the present time, RETMA committee SQ-11.1.1 is in the midst of preparing a joint comment on military waveguide flanges in an effort to clean up these dimensional problems.

Many contact flange designs have been evolved, their design having been dictated mainly by mechanical considerations. To effect a measure of standardization, the SQ-11.1.1 committee initiated a program several years ago to standardize on a series of miniature, unpressurized, contact flanges for use in complex waveguide assemblies as a means for connecting subassemblies internally. This procedure would allow for greatly simplified production and maintenance. The committee reviewed all of the various contact flange designs in existence, and decided on the outline shown in Fig. 3 and Table III (opposite). It is expected that this flange design will become an official RETMA standard by the end of 1956. This flange design does not use alignment pins, metal contacting fingers, or special gasketing. It has been found that a carefully machined surface of 63 microinches or better will yield excellent electrical results over the frequency range of 2.6 to 12.0 kmc and is economical to produce. By mounting the screws close to the waveguide and paying particular attention to the contact between the broad dimensions of the waveguides, a simple and economical waveguide connector design which yields a high order of performance has been obtained. Calculations and measurements have indicated that the mismatch contributions from a pair of properly mated contact flanges should be within 1.003 with the tolerances as specified. Predrilled flange blanks cannot be used due to the waveguide tolerances; therefore, the assembly procedure involves mounting a blank flange to the waveguide tubing by brazing or casting and then drilling after assembly. These flanges are asexual clearance, or tapped depending upon the particular mechanical requirements of the waveguide assembly, with one drill jig accomplishing all these operations. The design of this series of unpressurized contact flanges was done principally by A. F. Pomeroy of the Bell Telephone Laboratories.

To meet the needs for a pressurized version of the miniature contact flange, the SQ-11.1.1 committee has begun a program for the development and standardiza-



(a) (b)

(a)—Notes:

1) After soldering and before machining holes, inside dim. of tubing at the flange shall be made to agree to dims. and tolerances shown as U and V and as per TR_{-108}. For centering tolerance of U' and V' see Y.
2) Surface B shall not exceed 63 rms microinches per ASA B_{46} surface roughness standard. X pertains to the whole flange face including end of waveguide.
3) R corner radius may be replaced by chamfer as shown at C.
4) Decimal tolerance ± 0.004 except where otherwise noted.
5) NC_{-2} tap refers to class 2 fit as specified in American Standard B-1.1.
6) Angular tolerance $\pm\frac{1}{2}°$.
7) Y tolerance on waveguide inner dimension per RETMA TR-108-A.
8) Break edge or slightly countersink all holes on mating surface.
9) Deburr edges Z.

b)—Notes:

1) The inside dimensions of the waveguide tubing U and V at the flange shall be made to agree to the dimensions and tolerances of waveguide tubing as per RETMA standard TR-108-A.
2) Tolerance on waveguide inner dimensions U and V as per RETMA TR-108-A.
3) Surface B shall not exceed 63 microinches per ASA, B46 surface roughness standard. X pertains to the flatness of the whole flange face including end of waveguide.
4) R corner radius may be replaced by chamfer as shown at C. Tolerance $\pm 1/64$.
5) Decimal tolerance ± 0.004 except where otherwise noted.
6) UNC-2B fit shall be as specified in American Standard ASA B.1.1.
7) Break edge or slightly countersink all holes on mating surface.
8) Deburr outside edges.
9) Refers to waveguide opening.
10) Angular tolerance $\pm 1/4°$.

Fig. 3—(a) Miniature, unpressurized contact flanges, RETMA for WR 229 to WR 90.
(b) Miniature, unpressurized contact flange WR 284, 12 hole.

TABLE III
DIMENSIONS FOR MINIATURE, UNPRESSURIZED CONTACT FLANGES**

WR	229	187	159	137	112	90	WR
A	0.138–32 NC-2 Tap (See Note 5)						
B	0.147	0.147	0.147	0.147	0.147	0.147	B
C	0.922	0.810	0.699	0.643	0.553	0.470	C
D	1.422	1.215	1.061	0.965	0.830	0.705	D
E	1.922	1.620	1.423	1.287	1.107	0.940	E
F	2.844	2.430	2.122	1.930	1.660	1.410	F
*G	1 37/64	1.392	1 1/4	1.142	1.007	0.882	G
*H	3 5/32	2.784	2 1/2	2.284	2.014	1.764	H
J	0.438	0.247	0.184	0.247	0.237	0.230	J
K	0.844	0.715	0.663	0.590	0.571	0.455	K
L	1.250	1.183	1.142	0.933	0.797	0.680	L
M	1.688	1.430	1.326	1.180	1.034	0.910	M
*N	1	0.892	7/8	0.767	0.694	0.632	N
*P	2	1.784	1 3/4	1.534	1.388	1.264	P
*R	1/8	0.125	1/8	0.125	0.065	0.065	R
S	0.200	0.200	0.200	0.200	0.200**	0.200**	S
T ***	0.250	0.250	0.250	0.250	0.250**	0.250**	T
U ***	2.290	1.872	1.590	1.372	1.122	0.900	U
V ***	1.145	0.872	0.795	0.622	0.497	0.400	V
U' ***	1.145	0.936	0.795	0.686	0.561	0.480	U'
V' ***	0.5725	0.436	0.3975	0.311	0.2485	0.200	V'
X	0.0005	0.0005	0.0002	0.0002	0.0002	0.0002	X
Y	0.005	0.005	0.004	0.004	0.004	0.003	Y

* Indicates a tolerance of ± 0.018.
** Aluminum and other than light alloy material for brass flanges dimensions S 0.145 dimension T 0.188.
*** For tol. see "Y," note 7.

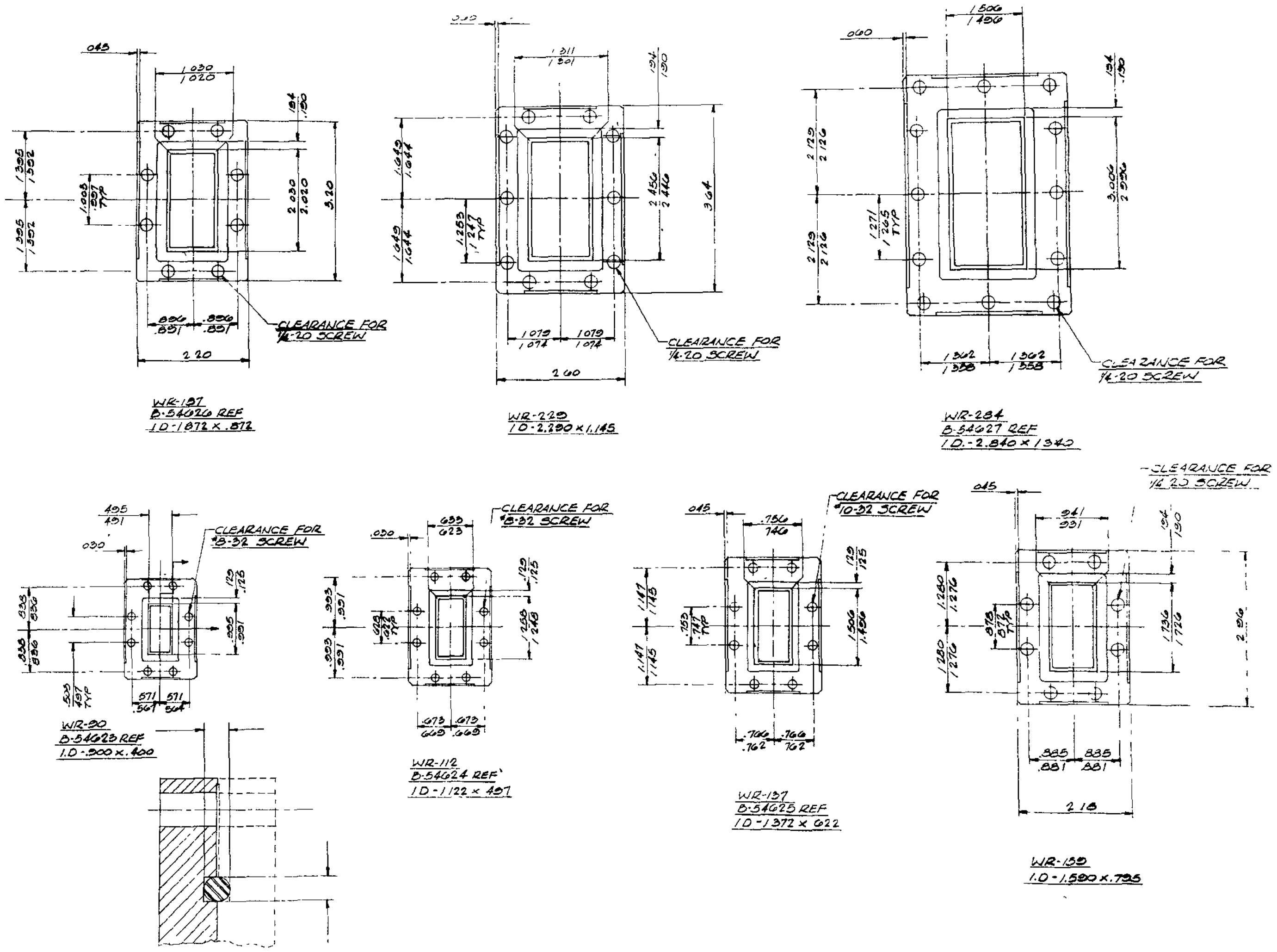


Fig. 4—Pressurized contact flange proposed.

tion of an asexual pressurizable contact flange. Fig. 4 shows a proposed design for such a flange. Because of mechanical problems, it was felt that it would be better to use through clearance holes and nuts and bolts to make the connection. Half of the gasket groove (in depth) is machined into each flange, thereby preserving the asexual characteristic. It is hoped that a standardized version of the pressurizable miniature contact flange will be arrived at within a year or two, since the waveguide designer faces a difficult problem in choosing the right flange design from the large number in existence. In the larger sizes of waveguide, contact flanges, both pressurized and unpressurized, are in use; however, the standardization here is far from complete.

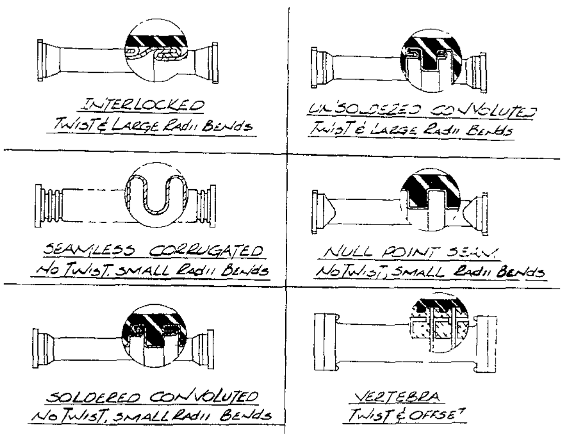
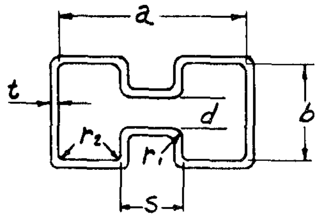


Fig. 5—Flexible waveguide types.

Flexible Waveguide

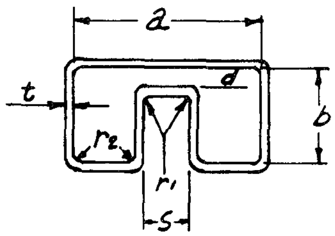
Flexible waveguide is essentially a rectangular corrugated metal hose assembly which provides for motional joints and tolerance build-up. The basic types of flexible waveguide are as follows: 1) soldered and unsoldered convoluted; 2) seamless split construction (single seam along each of the narrow edges of the waveguide); 3) interlock; 4) null point seam; and 5) vertebra. Fig. 5 illustrates the basic features of each type. With the exception of the interlock, all of the types listed above rely upon the mechanical flexure of the convolutions for motion. The interlock construction depends on the slipping of the joints to provide mechanical motion. Considerable development work has been done on flexible waveguide by several firms, and at the present state of the art, no real penalty is involved in using flexible waveguide. In fact, flexible waveguide which has a peak power capacity in excess of standard rigid waveguide and mates directly with the standard rigid

TABLE IV
MODERATE BANDWIDTH DOUBLE RIDGE WAVEGUIDE



Ridge Guide (Airtron No's)	Frequency Range		Dimensions							Attenuation db/ft Midband Aluminum	Peak Power Handling Capability
	Series A	Series B	a	b	d	s	t	r1	r2		
ARA-1109	1.00 to 3.00		3.600	1.800	0.540	1.130	0.125	0.125	0.045 max.	0.0097	14,000
ARA-174		2.0 to 4.5	2.500	1.250	0.500	0.785	0.080	0.080	0.03 max.	0.021	7,000
ARA-148	2.6 to 5.2		1.750	0.875	0.350	0.555	0.080	0.080	0.03 max.	0.032	3,400
ARA-133		4.7 to 11.0	1.025	0.475	0.191	0.256	0.050	0.060	0.03 max.	0.06	900
ARA-136	5.2 to 9.6		1.222	0.611	0.403	0.351	0.064	0.060	0.03 max.	0.05	1,300

TABLE V
EXTREMELY BROADBAND SINGLE RIDGE GUIDE



Ridge Guide	Frequency Range		Dimensions							Attenuation db/ft Midband (Al.)	Peak Power Handling Capability
	Series A	Series B	a	b	d	s	t	r1	r2		
50375	1.0 to 4.0		3.047	1.371	0.200	0.669	0.080	0.016	0.031	0.05	1500
50376	3.75 to 15.0		0.8125	0.3655	0.05315	0.1784	0.100	0.005	0.008	0.20	35
50437	10.0 to 40.0		0.306	0.133	0.0215	0.072	0.060	0.005	0.008	0.80	5

guide is now available. Attenuation of flexible waveguide is slightly higher than that of rigid guide; however, the mismatch contribution from well-designed flexible waveguide amounts to less than 1.05 in most cases. Flexible waveguide is usually protected by an elastomeric jacket generally made of neoprene or plastisol bonded to the outside surface of the guide. Flexible waveguide sections are available preformed to any desired shape or in standard straight lengths which are in multiples of six inches for field assembly use.

RIDGED WAVEGUIDES

Practically all of the preceding material applies to ridged waveguide as well as to rectangular waveguide. Tolerances, materials, and constructional techniques are basically the same for ridged waveguide as rectangular waveguide. The connectors used are also similar; however, contact flanges are almost universally used with ridged waveguide due to the problems encountered in designing chokes for the broad bandwidths obtainable with ridged guide. Flexible ridged waveguide is also available in certain sizes.

The big advantage in the use of ridged waveguide is the extremely wide bandwidth obtainable between the TE_{10} and TE_{20} mode cutoff wavelengths. Frequency ranges of four to one or more for the fundamental mode of operation are easily obtainable with single and double ridged waveguide. It is also useful in that the lowered cutoff frequency permits a more compact cross section, and the wave impedance is lowered. Tables IV and V show the basic construction of some special single and double ridged waveguides. Single ridged and double ridged waveguides achieve the same effect; however, the choice between the two depends on the application and mechanical considerations. Double ridged guide is preferred for long transmission lines since the depth of each ridge is roughly half that of a single ridge. This fact makes it easier to hold tolerances on the ridge, and flexible waveguide becomes simpler to fabricate. Single ridged guide is more practical for transitions to coaxial line and certain other specialized applications.

The ARA-136 double ridged waveguide shown in Table IV has found extensive use as a transmission line for commercial airlines weather radar, since C- and X-band radars may be used with the same transmission line in the aircraft. Also, the cross sectional dimensions are considerably less than that of standard C-band waveguide, thereby representing a considerable saving in space and weight for C-band installations.

Ridged waveguides cannot be analyzed by the simple methods of ordinary rectangular waveguide, and publications giving design data and theory of operation are quite limited.[1-3] Of these publications, the article by Hopfer gives the most advanced and accurate information. This article deals primarily with single ridged guide, although there is considerable design information also given for double ridged waveguide. Cohn's article includes design curves which can be used for both single and double ridged guide, but the data is not as accurate as Hopfer's, mainly because the step discontinuity susceptance effect is not included in the calculations.

Waveguide Assembly Constructional Techniques

Brazing

Brazed assemblies are still the most common type, although brazing is not necessarily the best method of fabricating waveguide assemblies. In this method, most of the parts are made from machined details and the entire assembly is brazed together generally by hand methods. With the large use of airborne radars, aluminum waveguide has become a major part of the production of waveguide components. Because of the fact that the melting point of aluminum brazing alloy is only 40 degrees lower than the melting point of the aluminum itself, hand brazing is a tricky and difficult job. It is also difficult to control the amount of distortion which occurs due to uneven heating. Therefore, hand brazing techniques should be confined to the relatively simple waveguide assemblies. Salt bath dip brazing techniques do much to eliminate the distortion problem and they also eliminate much of the flux entrapment which leads to corrosion problems. As a result, dip brazing methods are used for the more complicated assemblies. Extremely precise components can be produced by this method by the use of broached waveguide in conjunction with furnace brazing and suitable jigging techniques. An example of this technique is the precision crossguide directional coupler shown in the lower right hand corner of Fig. 6.

[1] S. B. Cohn, "Properties of ridge waveguide," Proc. IRE, vol. 35, pp. 783–788; August, 1947.

[2] Nathan Marcuvitz, "Waveguide Handbook," M.I.T. Rad. Lab. Series, vol. 10, pp. 399–402.

[3] Samuel Hopfer, "Design of ridged waveguides," IRE Trans., vol. MTT-3, pp. 20–29; October, 1955.

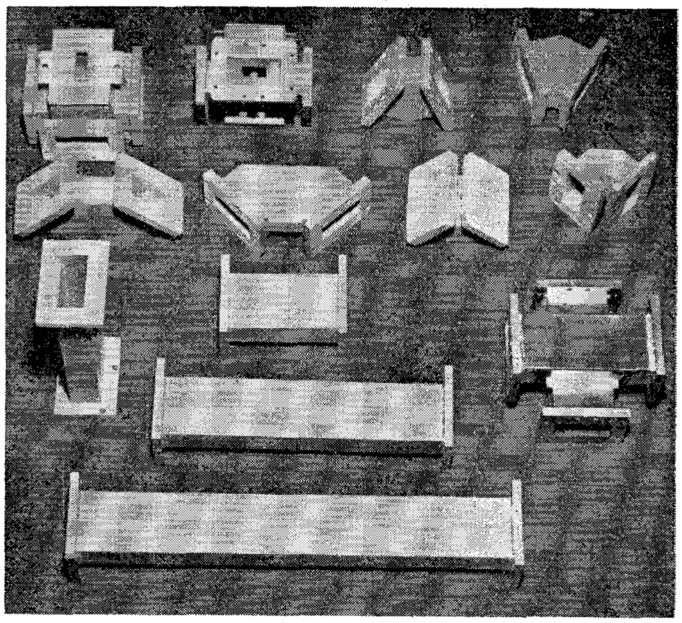


Fig. 6—Precision waveguide assemble fabricated by casting (upper) and by brazing and broading (lower).

Precision Casting

If a waveguide assembly is being produced in quantity, or if the complexity of the assembly increases beyond a certain level, it then becomes more economical to tool up for precision casting. The methods used most often for this application are plaster casting, the lost wax process, and die casting. The plaster and lost wax methods yield about the same order of precision (0.003 /inch) and are used in the majority of applications. Casting tools for die casting are relatively expensive and their use is limited to production of quantities in excess of several thousand.

Once the tools are worked out to give the proper dimensions, precision casting methods can readily duplicate parts economically in any quantity, whereas machining methods become very costly in comparison. Another advantage in casting is that adjustments can be made easily in the casting tools, thereby providing a means for finalizing the design right in the casting tools. This is an important advantage because, in precision waveguide assemblies, it is extremely difficult to translate the dimensions of a machined part to a set of drawings and then retranslate these every time a new part is produced. Fig. 6 also shows some waveguide components which have been produced by precision casting techniques.

Electroforming

Electroformed parts have found acceptance in some applications for complex and precise internal details, but the cost of electroforming is much higher than precision casting. Fig. 7 shows an electroformed hybrid ring circuit for X band; however, electroforming is more useful for applications in the millimeter wavelength region where the surface conductivity and roughness of normal casting alloys introduce severe attenuation.

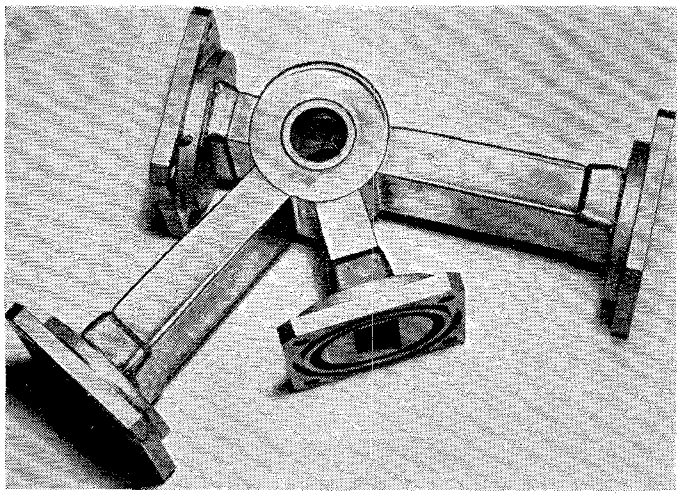


Fig. 7—Rat-race duplexer, electroformed.

With carefully machined and polished mandrels, an excellent surface finish can be obtained by electroforming. Furthermore, the purity of the metal is high, thereby providing good conductivity. There are, however, several difficulties encountered with electroforming. If the basic waveguide sections are electroformed and the flanges attached by brazing, distortions occur which nullify the inherent precision of electroforming. This problem can be eliminated by the expensive method of electroforming the flanges in place. Another serious problem is the reverse corner build-up that occurs as a result of the masking at the corners. This results in weak spots at the junctions of the flanges and electroformed waveguide. This problem can be alleviated by the use of suitable plastic compounds over the outer surfaces and by using special electrodes to "throw" metal into these corners. It must also be remembered that the electroforming process is only as accurate as the mandrel used, and therefore, the mandrel itself must be made to the tolerances required in the final product.

Pressurization of Waveguide for High Power

One of the major problems facing radar systems designers today is the ever increasing peak power which is becoming available. In order to increase the power handling capability of waveguide components, pressurization must be introduced. Unfortunately, rectangular waveguide is almost the poorest possible shape for pressure vessel design, and the standard wall thickness of waveguides larger than X band are far from adequate in this respect. Only a nominal amount of pressure can be applied without seriously distorting the waveguides. For example, pressures in excess of 5 psi will cause trouble in WR-650, especially since the tubing is usually in the annealed condition as a result of brazing. In the S-band region, 15 to 20 psi pressure is about the maximum for standard waveguide. At X band, pressures as high as 30 psi can be used with no difficulty. To meet the demand for high pressure waveguide in sizes larger than X band, a series of specially drawn waveguide tubing has been made available. This tubing was designed for negligible distortion at 60 psi pressure by using the principles outlined in Fig. 8.

Pressurization of waveguides for operation at extremely high altitudes and high power may not be the best choice, since the reliability of space born waveguide systems would be improved if pressurization could be eliminated. Of course, no voltage breakdown problems exist in the vacuum of outer space; however, the transition from the lower altitudes to outer space represents a serious problem. Towards this end, solid dielectric waveguide structures have been proposed and are under development.

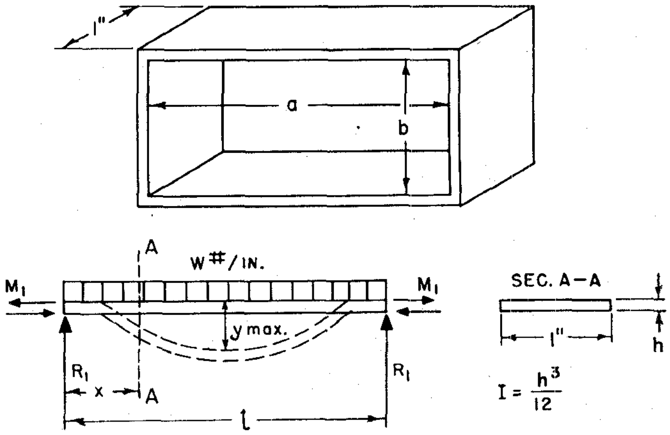


Fig. 8—Cross section of waveguide treated as uniformly loaded simple beam with end moments M_1.

General equation for deflection of pressurized waveguide:

$$EI\, y_{\max} = \frac{(a^3 + b^3)wl_2}{96(a+b)} - \frac{5wl^4}{384}$$

where

E = modulus of elasticity,
I = moment of inertia $= b'h^3/12$ where b' (in this term) $= 1$ inch width of waveguide section chosen,
$y_{\max}$ = maximum deformation of pressurized waveguide section which occurs at the center of the face,
a = internal dimension of wide face of waveguide,
b = internal dimension of narrow face of waveguide,
w = pressure since element was chosen as a beam 1 inch in width,
$l = a$, when calculating $y_{\max}$ for wide face,
$l = b$, when calculating $y_{\max}$ for narrow face.

Standardization

At the present time, because of the tremendous activity in waveguide systems, there is very serious need for further standardization in this field. The need for standardization of flange designs has already been discussed in the section on waveguide connectors. The increasing use of pressurization for high power systems requires a program for standardizing on heavy walled waveguide tubing, since the application of nominal pressures introduces severe distortion in standard size waveguides. The most pressing need for standardization is in the field of ridged waveguide, where the wide variety of parameters can result in many different waveguide structures all designed for the same application. A program for the standardization of ridge waveguide is now under way by the RETMA SQ-11.1.3 committee and it is hoped that a suitable standard will be arrived at within the next year or two.