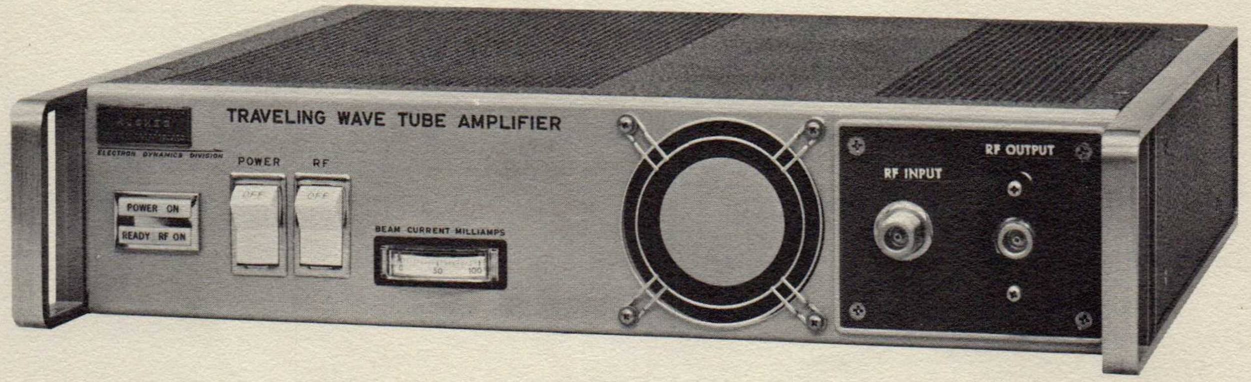
HUGHES

ELECTRON DYNAMICS DIVISION

1177H SERIES

INSTRUMENTATION TWT AMPLIFIERS



10 MODELS AVAILABLE FROM 1 TO 18 GHz . . .

- **1 to 2 GHz, 10 watts**
- **1.4 to 2.4 GHz, 20 watts**
- **2 to 4 GHz, 10 watts**
- **2.5 to 4 GHz, 20 watts**
- **4 to 8 GHz, 10 watts**
- **4 to 10.5 GHz, 10 watts**
- **8 to 12.4 GHz, 10 watts**
- **6.5 to 13.5 GHz, 10 watts**
- **12.4 to 18 GHz, 10 watts**
- **10.5 to 18 GHz, 10 watts**

FULL ONE YEAR WARRANTY – NO HOUR LIMIT

30 POUNDS IN A COMPACT CASE

DESCRIPTION

The ten models in the 1177H Traveling-Wave Tube Amplifier Series cover a 1 to 18 GHz frequency range with a minimum power output of 10 watts CW. Each amplifier consists of a PPM metal-ceramic traveling-wave tube, a regulated solid state power supply and complete air cooling system assembled within a compact instrument case.

The 1177H Series utilizes any of ten traveling-wave tubes developed for space applications. These tubes have logged over 1,000,000 hours in space on such vehicles as Surveyor, Mariner, Early Bird, Pioneer, ATS, Syncom, IntelSat, TACSAT, Lunar Orbiter and Apollo.

The knowledge gained in developing these "space" tubes allows us to warrant the complete amplifier package for a full year, regardless of the hours of use.

The 1177H's light-weight compactness makes it ideal for either bench or 19 inch rack mounting. This size-weight feature is the result of the unique circuit design.

Adding to the unit's versatility is the utilization of "plug-in" circuit boards which give the 1177H an extra dimension in ease of maintenance.

The 1177H has a wide variety of uses in such applications as EMI testing, taking antenna test patterns, communications, component testing, reflectometer systems, and general laboratory requirements.

SPECIFICATIONS*

RF PERFORMANCE

MODEL	FREQUENCY	POWER OUTPUT
1177H09	1.0 – 2.0 GHz	10 watts
1177H10	1.4 – 2.4 GHz	20 watts
1177H01	2.0 – 4.0 GHz	10 watts
1177H05	2.5 – 4.0 GHz	20 watts
1177H02	4.0 – 8.0 GHz	10 watts
1177H06	4.0 – 10.5 GHz	10 watts
1177H03	8.0 – 12.4 GHz	10 watts
1177H07	6.5 – 13.5 GHz	10 watts
1177H04	12.4 – 18.0 GHz	10 watts
1177H08	10.5 – 18.0 GHz	10 watts

ELECTRICAL

Gain at Rated Power Output	30 dB minimum**
Duty	CW
Input Voltage	120 VAC ±10%△
Input Frequency	50/60 Hz△
Power Consumption	250 W
Noise Figure	35 dB maximum
Spurious Modulation	–35 dB minimum
VSWR	3:1 maximum

MECHANICAL

Length	15.5 inches
Width	16.75 inches
Height	3.5 inches
Weight	30 pounds maximum
Connectors	Type N female†

ENVIRONMENTAL

Operating Temperature	0-50°C ambient

WARRANTY

One full year regardless of the hours of operation.

PROTECTIVE FEATURES

Automatic time delay
Helix current overload
Thermal overload
RF output connector interlock

TO ORDER SPECIFY

1177H	**01**	**F –**	**OOO**	**REPLACEMENT TUBES**
Series Number	**01** – 2.0 to 4.0 GHz **02** – 4.0 to 8.0 GHz **03** – 8.0 to 12.4 GHz **04** – 12.4 to 18.0 GHz **05** – 2.5 to 4.0 GHz **06** – 4.0 to 10.5 GHz **07** – 6.5 to 13.5 GHz **08** – 10.5 to 18.0 GHz **09** – 1.0 to 2.0 GHz **10** – 1.4 to 2.4 GHz	**F** – Front Panel Connector **R** – Rear Panel Connector	**OOO** – Standard Unit **XXX** – Factory Assigned Unit	564H 648H 771H 848H 564H(S) 648H(S) 771H(S) 848H(S) 417H 419H

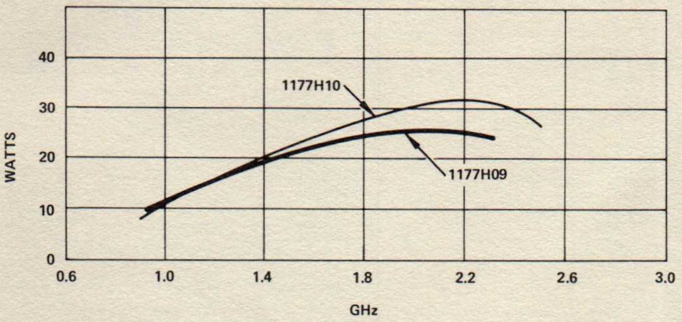
*Specifications subject to change without notice.

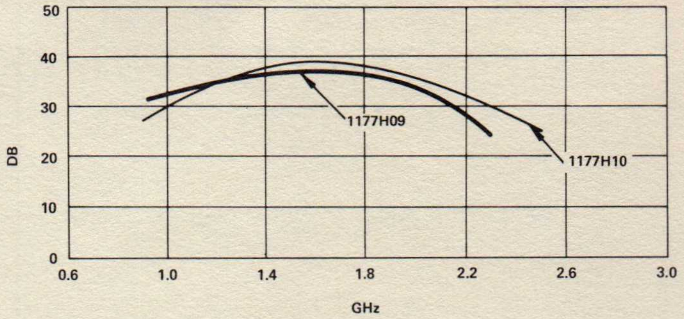
**Models 1177H06 and 1177H10 refer to typical performance curves for minimum gain.

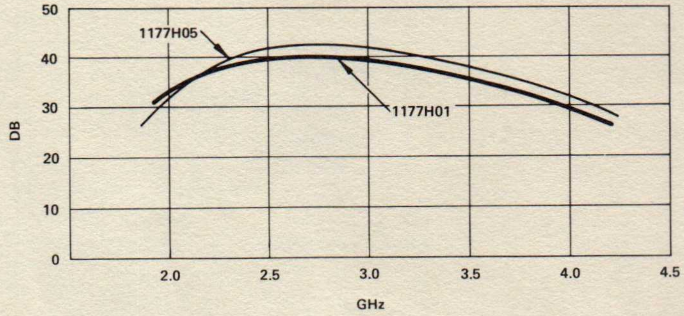
††Models 1177H04 and 1177H08 use a WR-62 waveguide with U/G-419/U flange as input and output connector and do not have an RF output interlock.

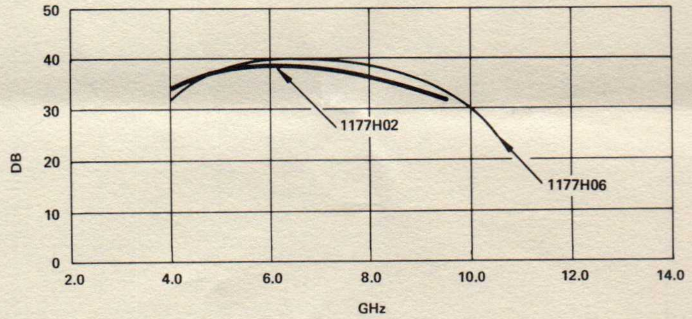
△ 230 VAC, 50 Hz available as an option.

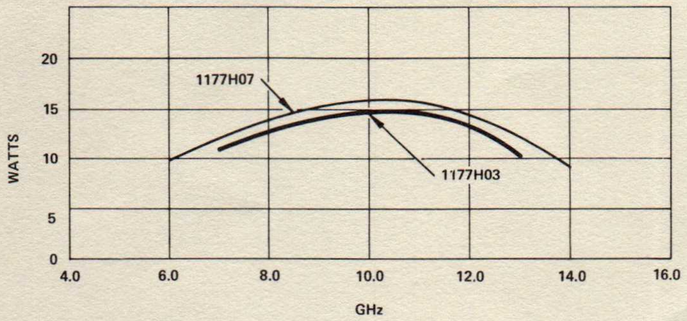
TYPICAL SATURATED Po AND GAIN
VS
FREQUENCY

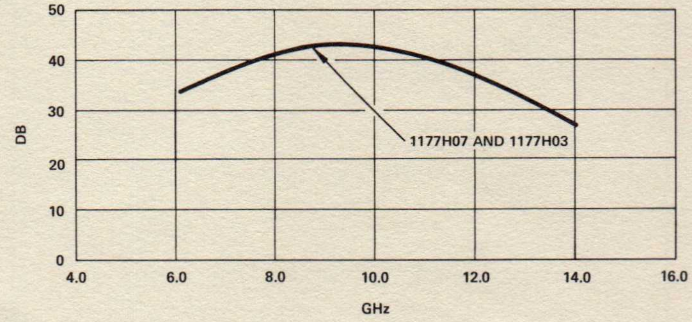


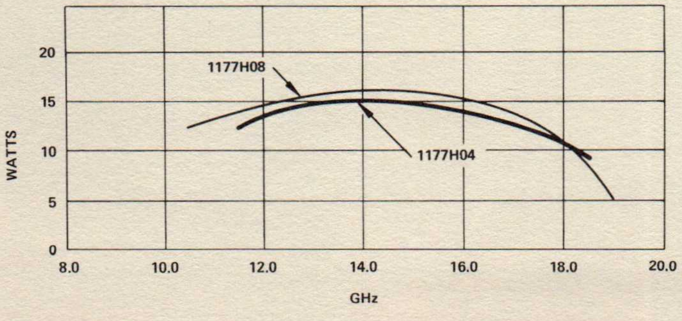


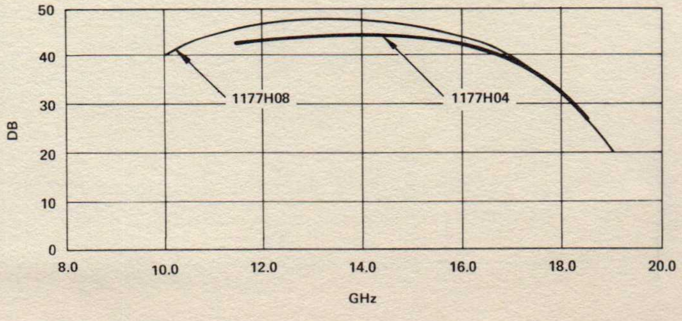












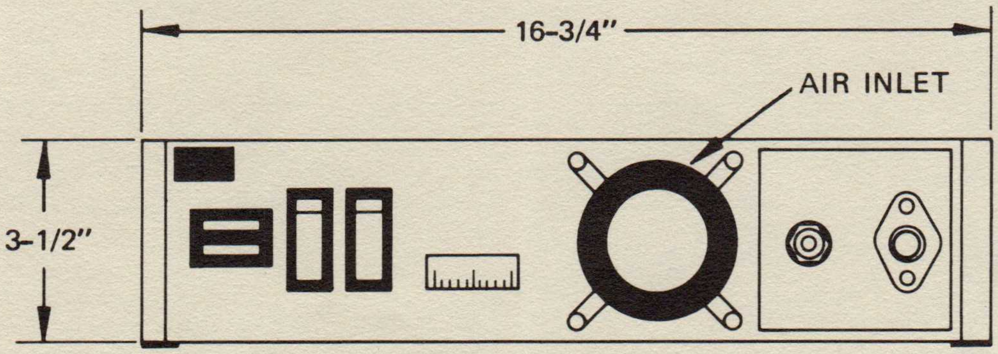
1177H SERIES

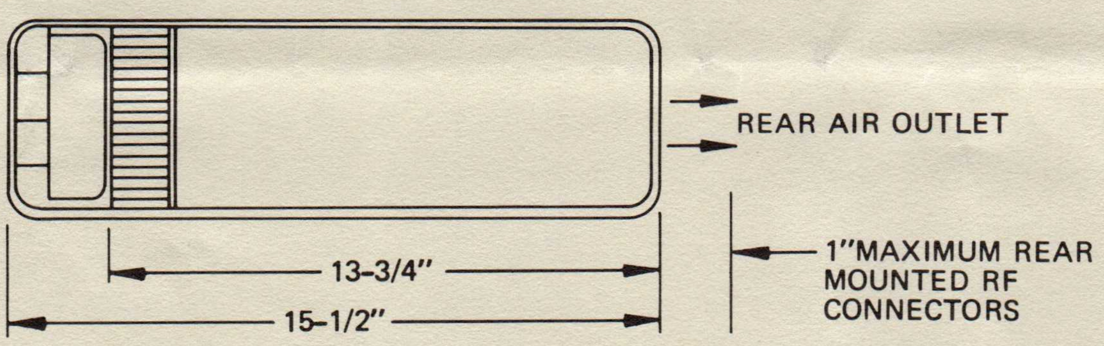
INSTRUMENTATION TWT AMPLIFIERS

HUGHES

ELECTRON DYNAMICS DIVISION

OUTLINE AND MOUNTING DRAWING





Specifications subject to
change without notice

Note: L-band units have a modified rear panel for tube protection. Complete details available upon request.

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ELECTRON DYNAMICS DIVISION / 3100 W. LOMITA BLVD. TORRANCE, CA. 90509 / TEL (213) 534-2121

Printed in U.S.A.—9-71

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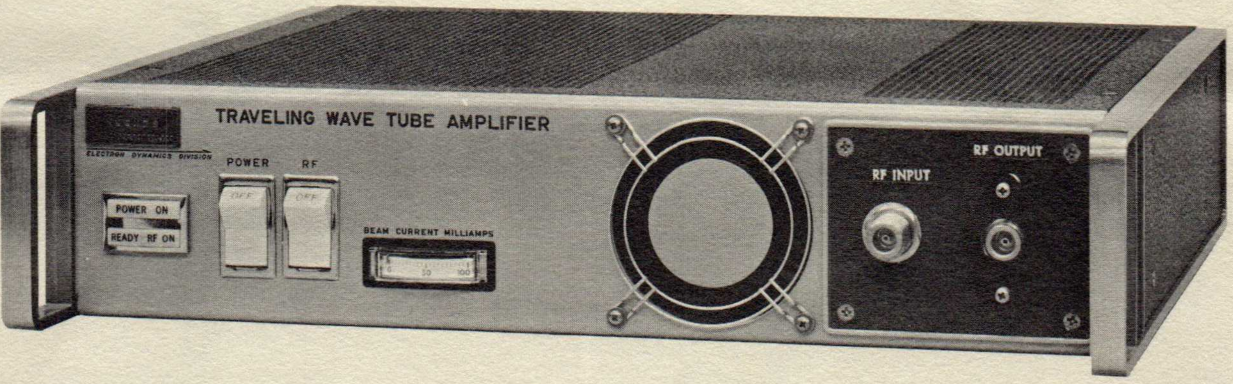
1177H03 SERIES

BROADBAND MICROWAVE AMPLIFIERS



DESCRIPTION

The Hughes 1177H03 Series of amplifiers were designed for communications and ECM applications. The series consists of three broadband instrumentation amplifiers providing coverage in the frequency range of 3.7 to 16.3 GHz. With a midband gain and power output in excess of 50 dB and 10 watts respectively, the amplifiers provide several watts of output power at the band edges.

Each amplifier features a solid-state power converter and metal-ceramic output traveling-wave tube similar in design to the tubes used in the Hughes communication satellites. They are completely protected, both thermally and electrically, with an internal air cooling system operating from 115 volts, 50/60 Hz, single-phase power.

These amplifiers weigh only 24 pounds, making them particularly suited for transportation to remote sites. They can be mounted in a 19-inch relay rack with a panel height of 3½ inches and a maximum depth of 20 inches. They carry a one-year warranty with no limit on the hours of operation.

SPECIFICATIONS*

RF PERFORMANCE

1177H03F** – 003

Frequency (GHz)	7.4	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
Power Output (min. w)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	5.0	5.0
Gain (min.)	30	30	30	30	30	30	30	30	24	22

1177H03F** – 005

Frequency (GHz)	3.9	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	11.7
Power Output	2.0	2.5	6.0	9.0	10.0	10.0	10.0	10.0	10.0	10.0
Gain (min.)	22	25	34	36	50	50	50	50	46	40

1177H03F** – 007

Frequency (GHz)	7.9	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.3
Power Output (min. w)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	5.0	5.0
Gain (min.)	30	30	30	30	30	30	30	30	24	22

ELECTRICAL

Duty	CW
Input Voltage	120 VAC ± 10% †
Input Frequency	50/60 Hz †
Power Consumption	250 W
Noise Figure	35 dB maximum
Spurious Modulation	–35 dB minimum
VSWR	3:1 maximum

MECHANICAL

Length	15.5 inches
Width	16.75 inches
Height	3.5 inches
Weight	30 pounds maximum
Connectors	Type N female

ENVIRONMENTAL

Operating Temperature	0-50°C ambient

WARRANTY

One full year regardless of the hours of operation.

PROTECTIVE FEATURES

Automatic time delay
Helix current overload
Thermal overload
RF output connector interlock

REPLACEMENT TUBES

1177H03F–003	785H01
1177H03F–005	785H02
1177H03F–007	785H01

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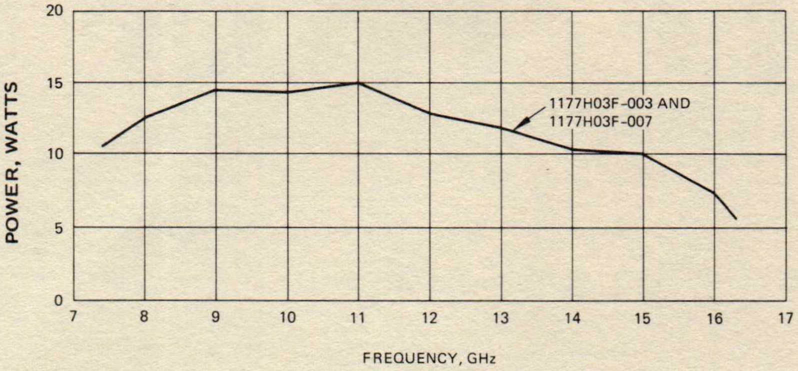
* Specifications subject to change without notice.

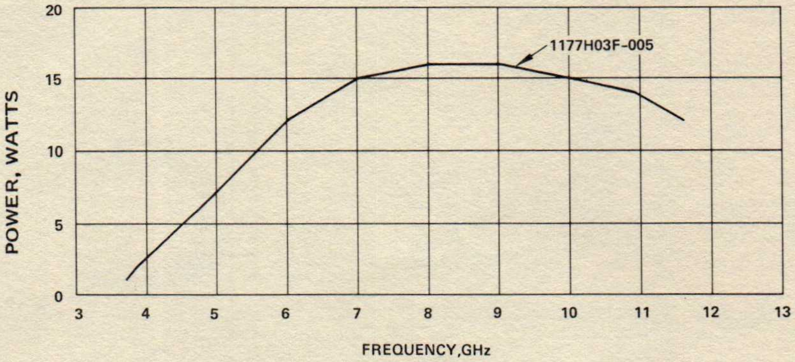
** For rear panel connector, use "R" in place of "F" when ordering.

† 230 VAC, 50 Hz available as an option.

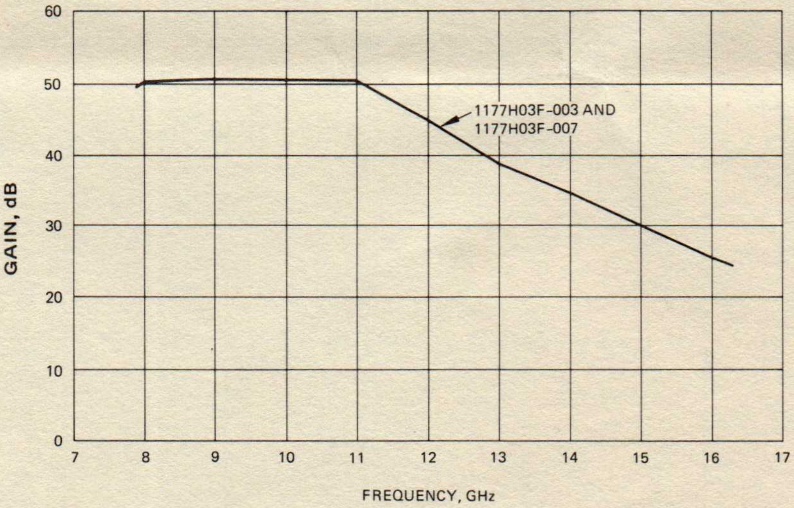
PERFORMANCE CURVES

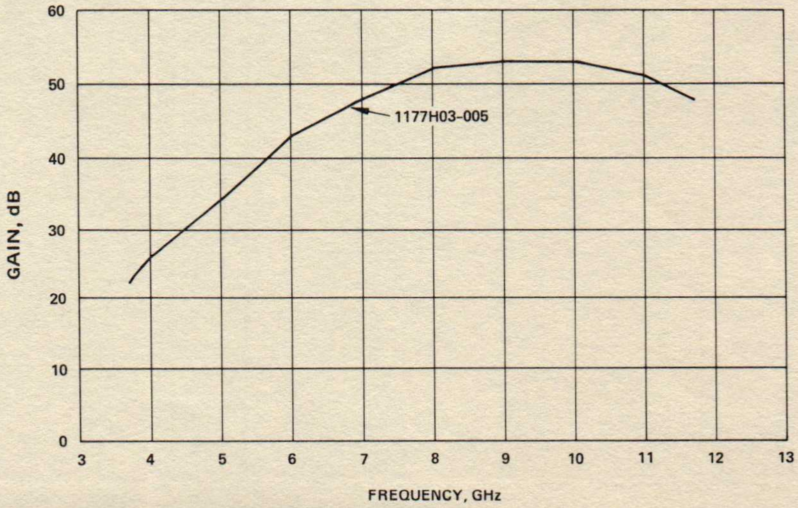
TYPICAL SATURATED POWER OUTPUT VERSUS FREQUENCY





TYPICAL SATURATED GAIN VERSUS FREQUENCY



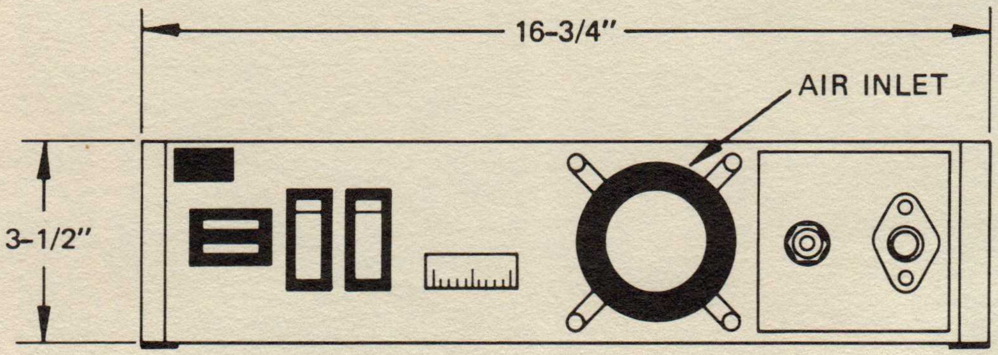


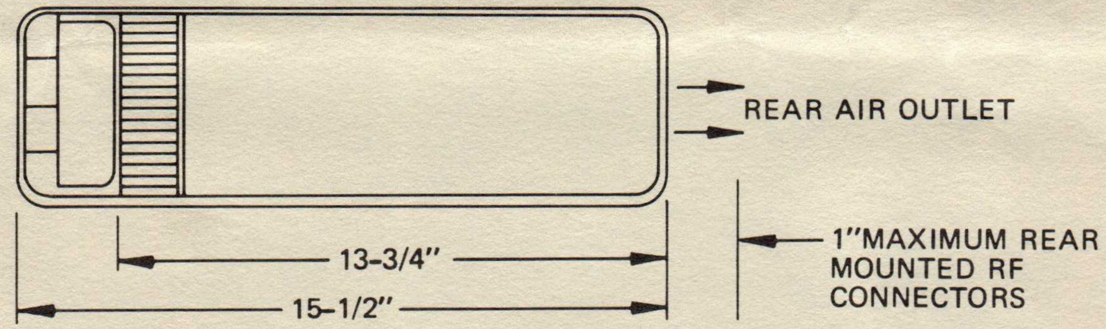
1177H03 SERIES
BROADBAND MICROWAVE AMPLIFIERS

HUGHES

ELECTRON DYNAMICS DIVISION

OUTLINE AND MOUNTING DRAWING





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Printed in U.S.A.– 2-72

HUGHES

ELECTRON DYNAMICS DIVISION

1277H SERIES

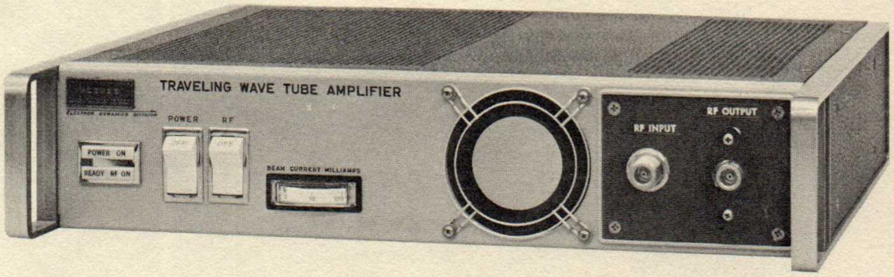
INSTRUMENTATION TWT AMPLIFIERS

5 MODELS AVAILABLE FROM 1 TO 18 GHz . . .

- **1 to 2 GHz, 20 watts**
- **2 to 4 GHz, 20 watts**
- **4 to 8 GHz, 20 watts**
- **8 to 12.4 GHz, 20 watts**
- **12.4 to 18 GHz, 20 watts**

FULL ONE YEAR WARRANTY – NO HOUR LIMIT

30 POUNDS IN A COMPACT CASE



DESCRIPTION

The five models in the 1277H Traveling-Wave Tube Amplifier Series cover a 1 to 18 GHz frequency range with a minimum power output of 20 watts CW. Each amplifier consists of a PPM metal-ceramic traveling-wave tube, a regulated solid state power supply and complete air cooling system assembled within a compact instrument case.

The 1277H Series utilizes any of five traveling-wave tubes developed for space applications. These tubes have logged over 1,000,000 hours in space on such vehicles as Surveyor, Mariner, Early Bird, Pioneer, ATS, Syncom, IntelSat, TACSAT, Lunar Orbiter and Apollo.

The knowledge gained in developing these "space" tubes allows us to warrant the complete amplifier package for a full year, regardless of the hours of use.

The 1277H's light-weight compactness makes it ideal for either bench or 19 inch rack mounting. This size-weight feature is the result of the unique circuit design.

Adding to the unit's versatility is the utilization of "plug-in" circuit boards which give the 1277H an extra dimension in ease of maintenance.

The 1277H has a wide variety of uses in such applications as EMI testing, taking antenna test patterns, communications, component testing, and general laboratory requirements.

SPECIFICATIONS*

RF PERFORMANCE

MODEL	FREQUENCY	POWER OUTPUT
1277H09	1.0 – 2.0 GHz	20 watts
1277H01	2.0 – 4.0 GHz	20 watts
1277H02	4.0 – 8.0 GHz	20 watts
1277H03	8.0 – 12.4 GHz	20 watts
1277H04	12.4 – 18.0 GHz	20 watts

ELECTRICAL

Gain at Rated Power Output	30 dB minimum
Duty	CW
Input Voltage	120 Vac ±10%**
Input Frequency	50/60 Hz**
Power Consumption	250 W
Noise Figure	35 dB maximum
Spurious Modulation	–35 dB minimum
VSWR	3:1 maximum

1277H SERIES

INSTRUMENTATION TWT AMPLIFIERS

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ELECTRON DYNAMICS DIVISION

MECHANICAL

Length	15.5 inches
Width	16.75 inches
Height	3.5 inches
Weight	30 pounds maximum
Connectors	Type N female†

ENVIRONMENTAL

Operating Temperature	0-50°C ambient

WARRANTY

One full year regardless of the hours of operation.

PROTECTIVE FEATURES

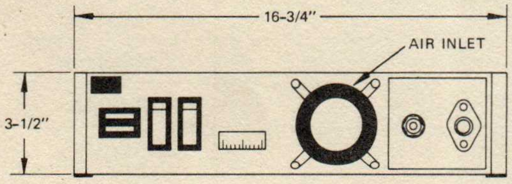
Automatic time delay
Helix current overload
Thermal overload
RF output connector interlock

TO ORDER SPECIFY

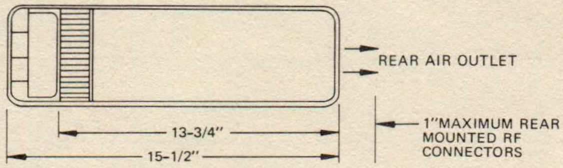
1277H	01	F –	000	REPLACEMENT TUBES
Series Number	**01 –** 2.0 to 4.0 GHz	**F –** Front Panel Connector	**000 –** Standard Unit	568H
	02 – 4.0 to 8.0 GHz			640H
	03 – 8.0 to 12.4 GHz	**R –** Rear Panel Connector	**XXX –** Factory Assigned Special	783H
	04 – 12.4 to 18.0 GHz			856H
	09 – 1.0 to 2.0 GHz			418H

*Specifications subject to change without notice.
**230 VAC, 50 Hz available as an option.
†1277H04 unit uses a WR-62 waveguide with U/G-419/U flange as input and output connector and do not have an RF output interlock.

OUTLINE AND MOUNTING DRAWING



Specifications subject to change without notice



YOUR LOCAL REPRESENTATIVE

NOTE: L-band units have a modified rear panel for tube protection. Complete details available upon request.

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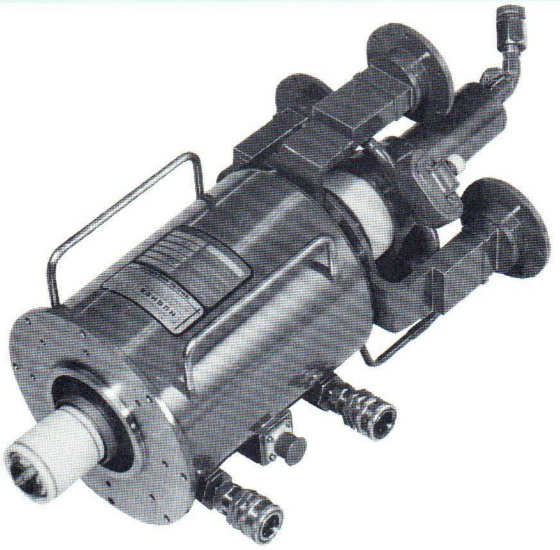
Printed in U.S.A.—9-71

Technical Data

614H

8kW C-BAND CW TWT



The 614H is a high gain metal ceramic traveling wave amplifier that is ideal for broadband satellite communications ground terminal transmitters. It covers the full communications bandwidth without electrical or mechanical adjustments, and is capable of over 10 kW CW operation and 30% efficiency using a depressed collector. It is of rugged and reliable design offering long life service.

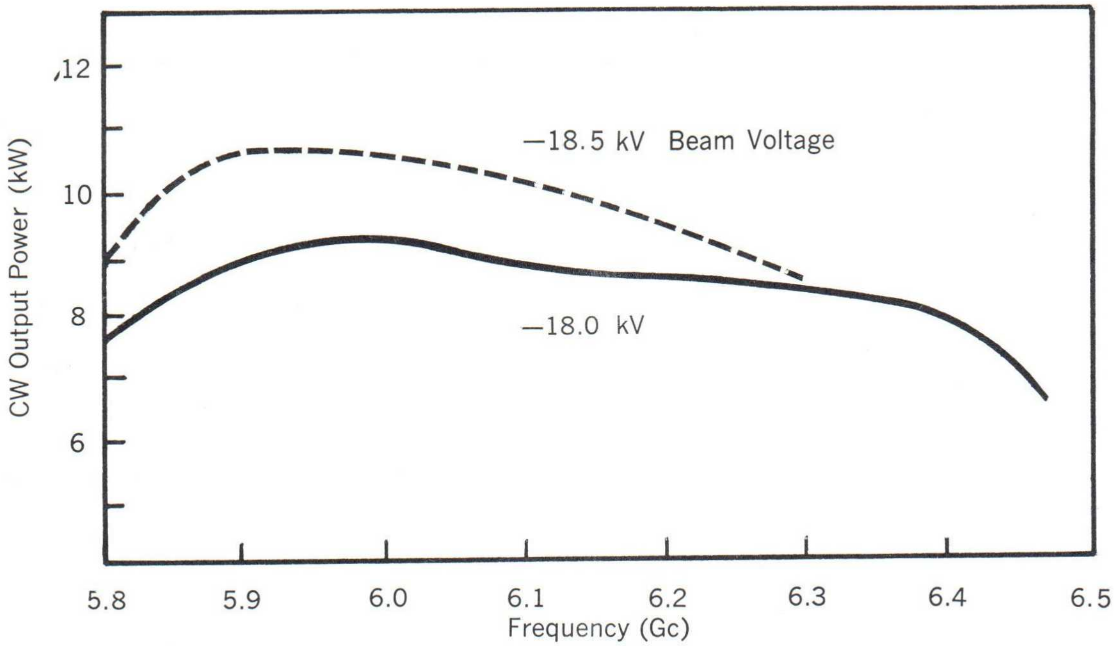
Preliminary Specifications

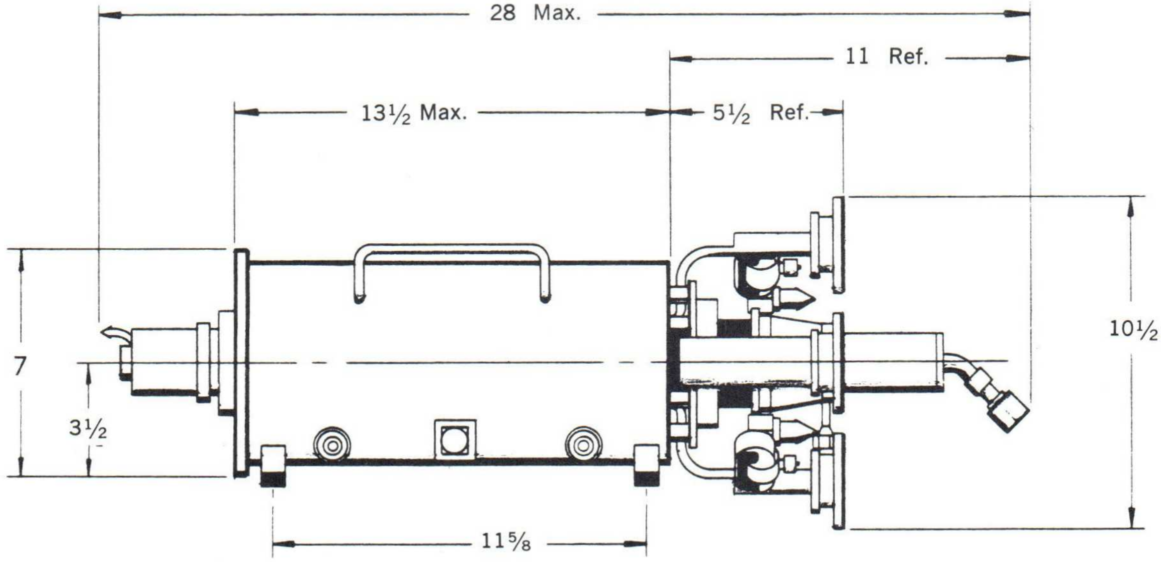
Frequency	5.925-6.425 Gc
RF Output Power	7-10 kW
Gain	40 dB
Duty	CW
Cathode Current	3A
Collector Voltage	0-8 kV
Solenoid Power	1500 Watts
Heater Voltage	10.5 V
Cooling: Collector	8 GPM of H_2O
Body	1 GPM of H_2O
Solenoid	2 GPM of H_2O
Size	28″ Long x 7″ Dia.
Weight: Solenoid	65 Lbs.
Tube	30 Lbs.

MICROWAVE TUBE DIVISION
11105 S. LA CIENEGA BOULEVARD, LOS ANGELES, CALIFORNIA 90009

HUGHES
HUGHES AIRCRAFT COMPANY

614H





These data are typical values. For operating instructions and electrical characteristics, contact our field engineers listed below.

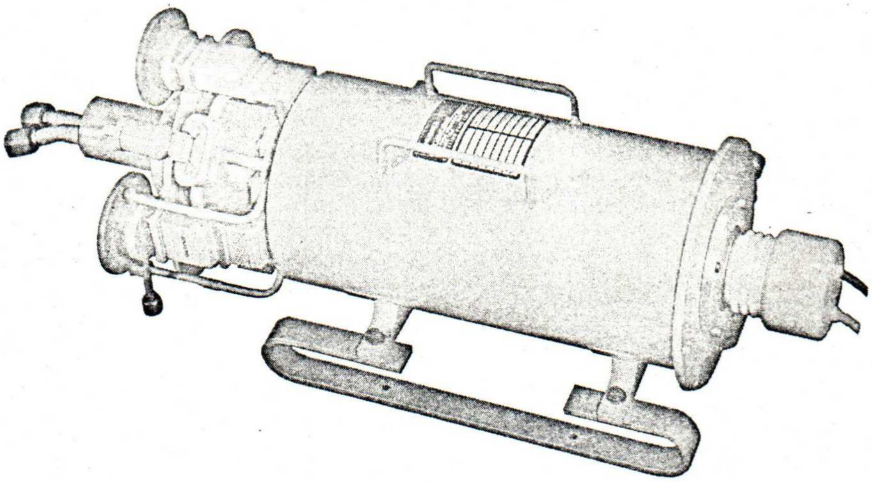
Los Angeles, Calif. 776-1515 Ext. 6661	Red Bank, N.J. 741-1259	Washington, D.C. 234-9300	Waltham, Mass. 862-6800

LITHO IN U.S.A.

Technical Data

614H

8 kW C-BAND CW TWT



The 614H is a high gain metal ceramic traveling-wave amplifier that is ideal for broadband satellite communications ground terminal transmitters. It covers the full communications bandwidth without electrical or mechanical adjustments, and is capable of over 10 kW CW operation and 30% efficiency using a depressed collector. It is of rugged and reliable design offering long life service.

SPECIFICATIONS

Frequency	5.925 - 6.425 GHz	Heater Voltage	11.0 V
RF Output Power	7 - 10 kW	Cooling: Collector	10 GPM of H_2O
Gain at Saturation	40 dB	Body	1 GPM of H_2O
Duty	CW	Solenoid	2 GPM of H_2O
Cathode Current	3.25 A	Size	30" Long X 12" Dia.
Collector Voltage	0 - 7 kV	Weight: Solenoid	85 Lbs.
Solenoid Power	2500 Watts	Tube	30 Lbs.

HUGHES

HUGHES AIRCRAFT COMPANY

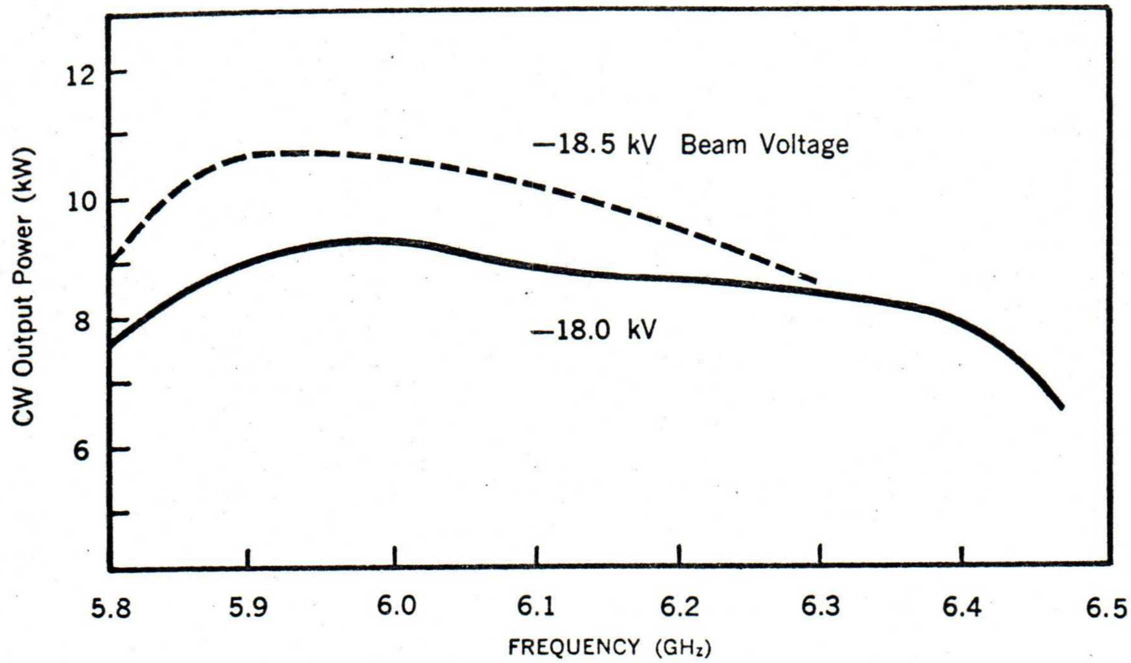
ELECTRON DYNAMICS DIVISION

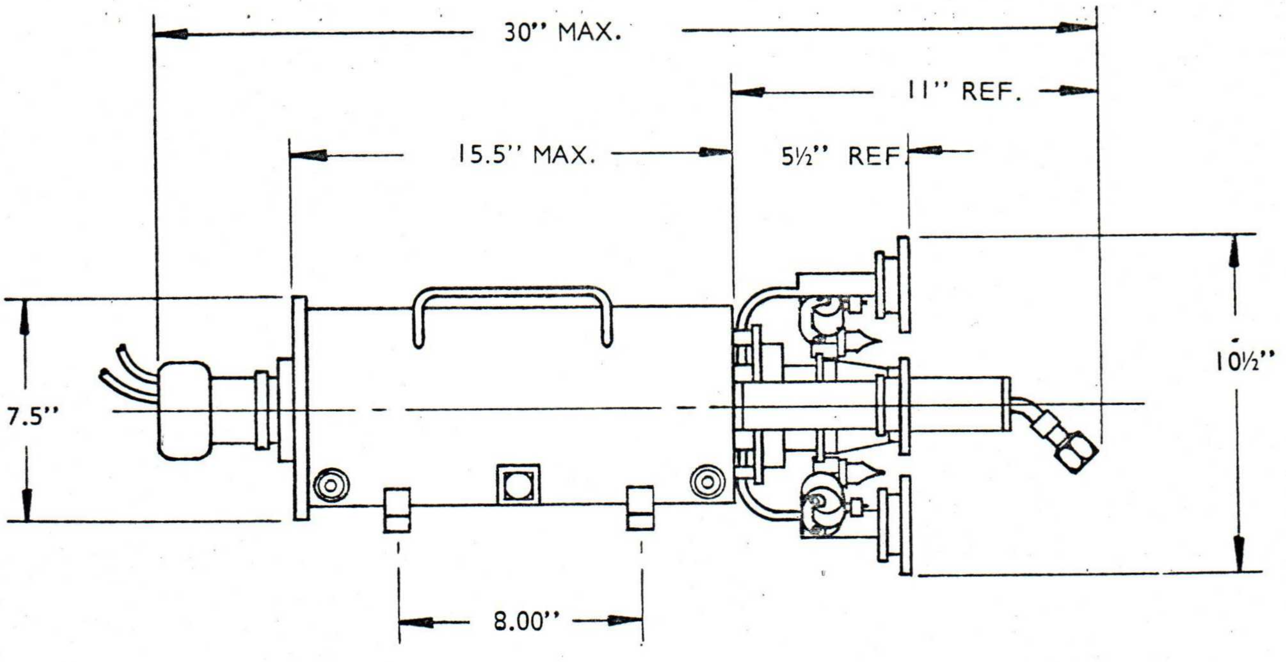
3100 WEST LOMITA BOULEVARD, TORRANCE, CALIFORNIA 90509

614H

HUGHES

HUGHES AIRCRAFT COMPANY





These data are typical values. For operating instructions and electrical characteristics, contact our field engineers listed below.

Los Angeles, Calif.	Eatontown, N. J.	Washington, D. C.	Lexington, Mass.
(213) OR 0-1515, Ext. 6728	(201) 741-1259	(202) 234-9300	(617) 861-0358

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CREATING A NEW WORLD WITH ELECTRONICS

HUGHES

HUGHES AIRCRAFT COMPANY
MICROWAVE TUBE DIVISION
LOS ANGELES 45, CALIF.

TEST SPECIFICATION

SPECIFICATION NO. B 151162-I

TUBE TYPE 614-H

REVISION B 13 January 1966

SUPERSEDES A 29 December 1965

APPROVED:

QUALITY CONTROL E L [illegible] 12/9/65
ENGINEERING A L Rousseau 12/9/65
R & D DEPT. [illegible] 12/9/65

MTD-1081/500/1BC/60

REVISIONS

REV.	DATE	DESCRIPTION & AUTHORIZATION	APPROVALS		
			QC	ENGR	MFG.
A	12/29/65	Description was Frequency 5.9 to 6.4 Gc, is Frequency 5.925 to 6.425 Gc, Weight was 95 pounds is Tube - 30 pounds Solenoid - 65 pounds Test Number 1.7 - added "Solenoid Power P_{sol} max. 2.0 kw Symbols - added P_{sol} - Solenoid Power	1/5/66 [illegible]	1/5/66 GTR	1/5/66 H.U.K.
B	1/13/66	Added note 8f.	[illegible]	1/14/66 GTR	1/14/66 H.U.K.

614-H SPECIFICATION

DESCRIPTION: Forward-wave amplifier, Frequency 5.925 to 6.425 Gc,
Power output 8kw., Duty CW, Solenoid focused,
Metal and Ceramic construction.

Mounting Position: Any

Cooling: Liquid (water) 8 gpm @ 50 psi pressure drop (collector)
Liquid (water) 1 gpm @ 30 psi pressure drop (body and window)
Liquid (water) 2 gpm @ 30 psi pressure drop (solenoid)

RF Connectors: Mate with RG 50/U waveguide cover flange

DC Connections: See outline drawing

Weight: Tube - 30 pounds
Solenoid - 65 pounds

Dimensions: See outline drawing

TEST NUMBER	TEST	SYMBOL	LIMITS		UNITS
			MAX.	MIN.	
1.0	INDIVIDUAL TESTS, Notes 1, 2, 3, 6 & 8				
1.1	HEATER				
** 1.1.1	Operating voltage	E_f	12.0	9.0	V
** 1.1.2	Operating current	I_f	6.0	3.0	A
1.1.3	Surge current Note 4	i_f	8.0		a
1.2	CATHODE				
** 1.2.1	Operating voltage	E_k	-15	-20	kVdc
** 1.2.2	Operating current	I_k	3.0		A
1.3	CIRCUIT				
1.3.1	Operating voltage - ground potential				
** 1.3.2	Operating current	I_w	.300		A
1.4	COLLECTOR				
1.4.1	Operating voltage	E_b	-500	-7000	Vdc
** 1.4.2	Operating current	I_b	3.0		A
1.5	ION PUMP (Note 5)				
1.5.1	Operating voltage	E_{ip}	3.3	2.7	kVdc
** 1.5.2	Operating current	I_{ip}	100		uA
1.6	RF POWER OUTPUT 8 kw Nominal				
1.6.1	Voltages and power input in accordance with Test Data Sheet f = 5.9 to 6.4 Gc	P_o		5.0	kW
1.6.2	RF power input	P_{in}	1.0		W
1.7	SOLENOID				
	Operating voltage	E_{sol}	150		Vdc
	Operating current	I_{sol}	20		A
	Solenoid Power	P_{sol}	2.0		kw

NOTES

1. Symbols:

Du - Duty cycle
E_b - Collector voltage
E_f - Heater voltage
E_{ip} - Ion pump voltage
E_k - Cathode voltage
E_{sol} - Solenoid voltage
f - Operating frequency of TWT
I_b - Collector current
I_f - Heater operating current
i_f - Heater surge current
I_{ip} - Ion pump current
I_k - Cathode current
I_{sol} - Solenoid current
I_w - Circuit current
P_{in} - RF power input
P_o - RF power output
VSWR - Voltage standing wave ratio
P_{sol} - Solenoid Power

2. The tube shall be tested at room ambient conditions with specified cooling. All operating tests shall be performed with the cathode potential, solenoid current, and filament potential required for optimum performance and specified on the Test Data Sheet.

3. The tube shall be turned on as follows:

   a. Apply rated ion pump voltage.
   b. Cool solenoid, body, and collector with specified coolant flow.
   c. Apply nameplate heater voltage, and allow five minutes for cathode to warm up.
   d. Apply solenoid current indicated on Test Data Sheet.
   e. Apply nameplate cathode voltage. } may be applied simultaneously
   f. Apply nameplate collector voltage }

4. Heater surge current is defined as the instantaneous value of heater current during the cathode warm-up period. It is the responsibility of the customer to limit this current to the maximum value specified.

5. It is recommended that voltage be applied to the ion pump at all times whether or not the tube is in use. Application at least every four (4) months during storage is required.

6. This traveling-wave tube will be damaged if it is operated with the RF input or output connectors either open-circuited or short-circuited. It is the responsibility of the user to provide isolators in both input and output waveguide transmission lines so that the VSWR presented to the tube is not greater than 1.25 to 1. The output isolator must be capable of handling the maximum average output power from the tube, and the input isolator must be capable of dissipating 10 watts of average power.

**7. Indicates test information to be supplied with each tube.

8. Extreme care should be taken in operating this tube due to the very high average power. Therefore, the following protective measures are recommended:

   a. Output waveguide arc sensing and body current overload circuitry must be used to remove the cathode voltage within 10 miliseconds if an arc occurs or the body current exceeds 300 ma. A vac-ion pump interlock system is required to turn off the tube within 10 ms. if the vac-ion current exceeds 10 ua.

   b. The tube must be turned on by applying the DC cathode voltage to between -17 ±1 kv within 100 milliseconds.Do not operate at voltages above -15 kv or below -20 kv.

   c. The tube must never be operated without the solenoid current. An interlock system should be used to prevent the cathode voltage from being turned on without the solenoid current.

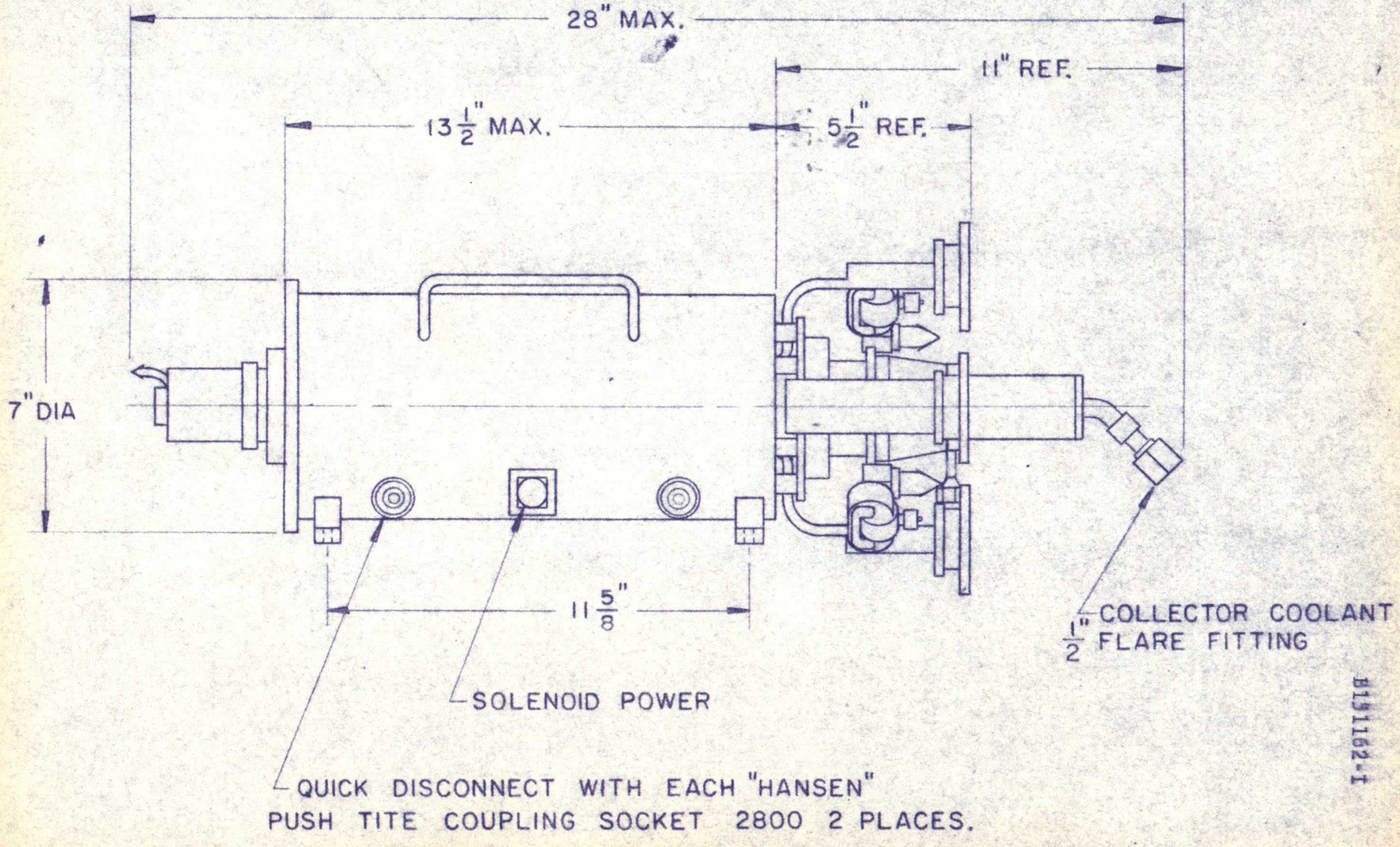
   d. A crowbar curcuit should be connected across the high voltage supply capable of disconnecting the high voltage from the cathode current within 10 microseconds.

   e. It is advisable to have a water-flow interlock switch which will prevent the turn-on of high voltage to the cathode if the water flows are below the required ratio. The input water temperature must be kept below 30°C.

   f. The heater voltage shall be held within ±5% of the nameplate value. Whenever the cathode voltage is left off for over 5 minutes, the heater voltage should be reduced by 10 percent.

614 H

OUTLINE & MOUNTING I



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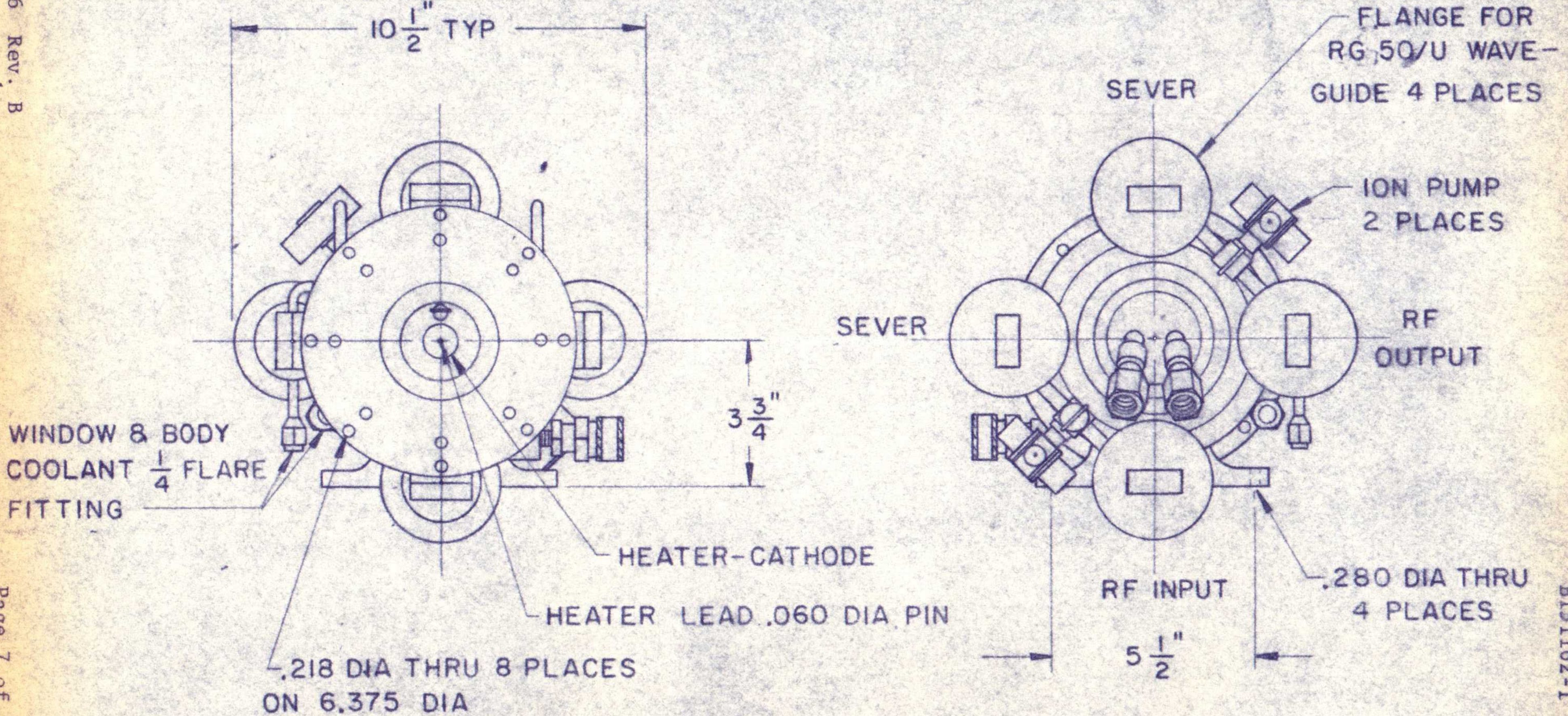
614 H

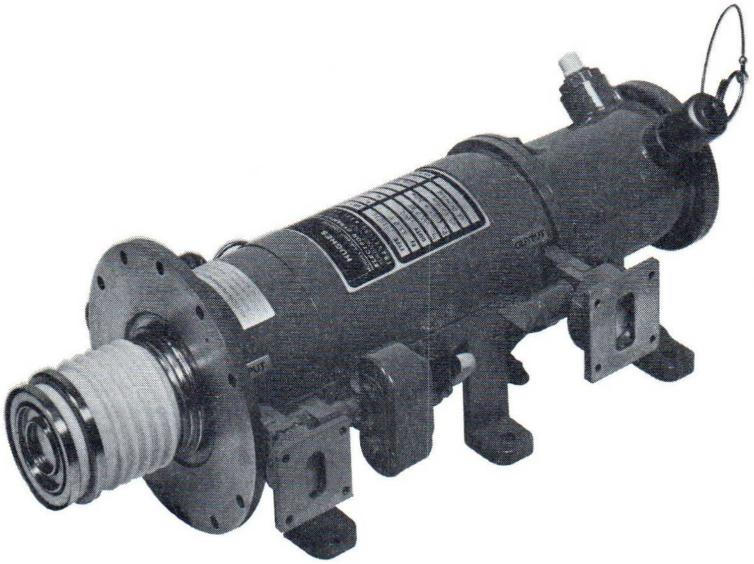
OUTLINE & MOUNTING II



Technical Data

760H

ENVIRONMENTALIZED
50 KW X-BAND
PULSED TWT



The 760H is a broad band, high power traveling-wave tube. This production type has high efficiency with high gain per unit length. Peak power of 50 kW and depressed efficiency of 30% are attained in this lightweight, liquid-cooled, alnico permanent magnet-focused TWT. The 760H is designed to meet MIL-E-5400 IA specifications.

SPECIFICATIONS

COLLECTOR VOLTAGE	−11.5 kV	FREQUENCY	8.9 – 9.9 GHz
HEATER VOLTAGE	11.0 V	POWER OUT	40 kW Minimum
HEATER CURRENT	4.0 A	DUTY	1%
WEIGHT	24 lbs.	GAIN	42 dB
LENGTH	16.5 in.	CATHODE VOLTAGE	−30.5 kV
COOLING	4.0 GPM FC-77 or equivalent	CATHODE CURRENT	8.0 A

Values are based on preliminary designs, and additional product refinement may be required for specific applications.

HUGHES
HUGHES AIRCRAFT COMPANY

ELECTRON DYNAMICS DIVISION
3100 WEST LOMITA BOULEVARD, TORRANCE, CALIFORNIA 90509

760H

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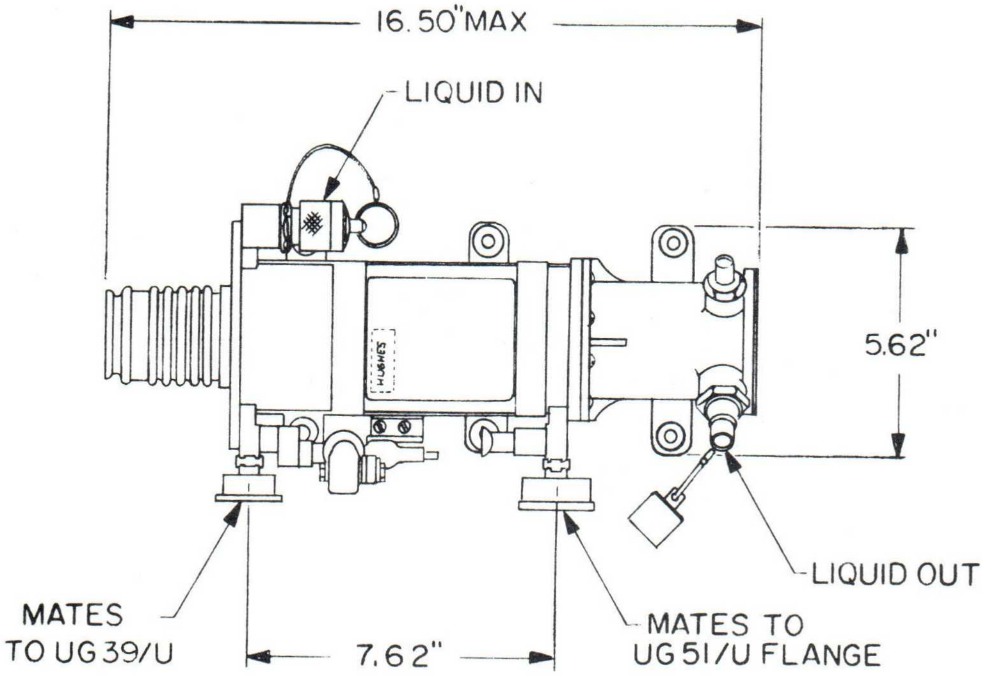

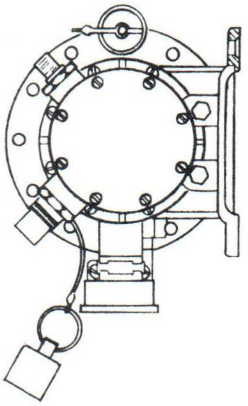

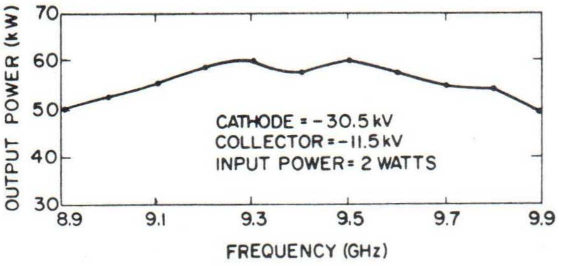

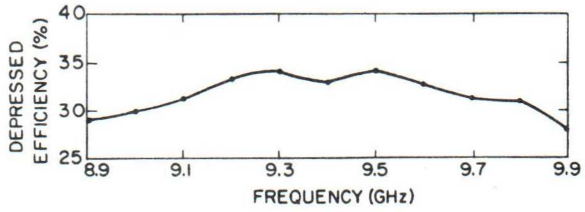

These are typical values. For operating instructions and electrical characteristics, contact our field engineers listed below.

HUGHES OFFICES

Torrance, Calif.
(213) 534-2121

Eatontown, N. J.
(201) 741-1259

Lexington, Mass.
(617) 861-0358

Washington, D. C.
(202) 234-9300

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3/69

HUGHES AIRCRAFT COMPANY

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MICROWAVE TUBE DIVISION

11105 S. LA CIENEGA BLVD. • LOS ANGELES 9, CALIFORNIA • TELEPHONE: SPRING 6-1515 ORCHARD 0-1515

JOINT ELECTRON DEVICE ENGINEERING COUNCIL

FORMAT FOR THE TWT DATA SHEET

ELECTRON TUBE TYPE: 7640/313H

All ratings are based on the ABSOLUTE system.

The 7640/313H traveling wave tube employing a helix type wave propagating structure is a power amplifier for operation in the 2000 to 4000 Mc frequency range. The power output is approximately 1000 watts with an average gain of 30 db and the tube is air cooled. It is designed for pulsed operation with a maximum duty cycle of .006. The input and output fittings are designed to mate with UG 19B/U type connectors. A permanent magnet provides the magnetic field and is integral with the tube.

ELECTRICAL DATA GENERAL	Units
Heater Voltage	6.3 Volts
Heater Current at 6.3 Volts	3.5 to 4.5 Amps
Cathode Pre-Heating Time (before application of beam voltages)	180 Sec.

MECHANICAL DATA GENERAL

Base and Physical Dimensions - See Outline Drawing
Mounting Information Any Position
Cooling Data 2 cfm of air
RF Input and Output Impedance and type connector 50-ohm, UG 19B/U
Weight - Approximately 17.5 lbs. (maximum)

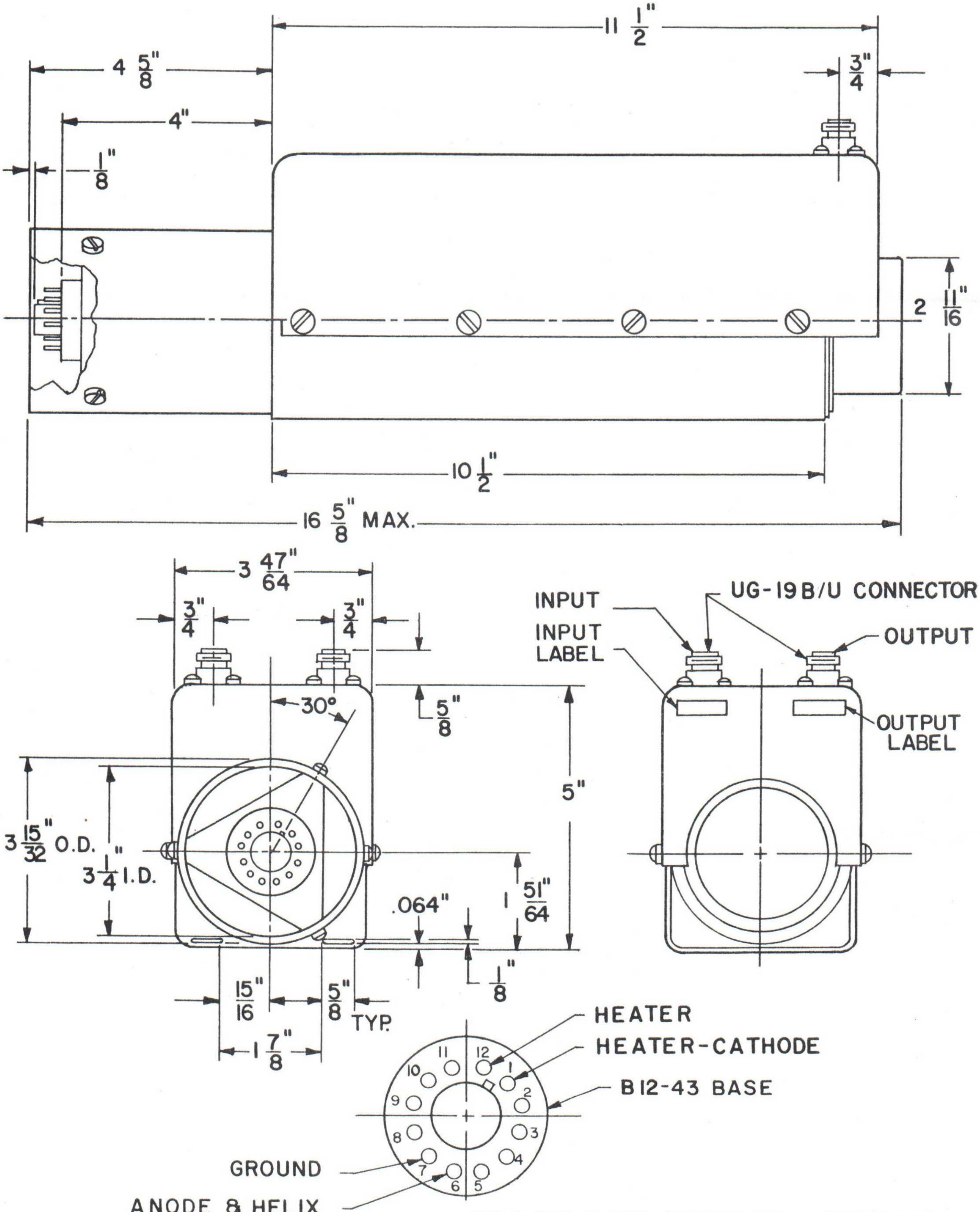
ABSOLUTE RATINGS	Units
Heater Surge Current	10 Amps
Heater-Cathode Voltage	-8000 Volts Max.
Cathode Current	2.0 Amps Max.
Helix Voltage	Ground
Helix Current	0.8 Amps Max.
Collector Voltage	Ground
Collector Dissipation	100 Watts Max.
Bulb Temperature	150° C
Input RF Power	2 Watts Max.
Duty Cycle	.006 Max.
Altitude	10,000 Ft.

TYPICAL OPERATION PULSED	Units
Focusing Field Strength	1350 Gauss
Operating Frequency Range	2 to 4 kMc
Cathode Current	1.4 Amps
Helix Voltage	Ground
Helix Current	0.5 Amps
Collector Voltage	Ground
Collector Current	0.9 Amps
Pulse Modulation Voltage	-7300 Volts
Gain (Saturated)	30 db
Gain (Small Signal)	33 db
RF Output (Saturated)	1300 Watts
Gross Small Signal Gain Variation	3 db
Saturated Power Variation	3 db
Input VSWR Cold	2.2 to 1 Max.

TYPICAL OPERATION	Units
Output VSWR Cold	1.5:1

NOTE: All voltages are referenced to the cathode.

313-H/7640



note: PINS 5 & 6 ARE CONNECTED INTERNALLY

26 December 1961 Rev. G

⑪ ~~⑯~~ T.P.D.

ELECTRON TUBE DIVISION
HUGHES PRODUCTS
LOS ANGELES 45, CALIFORNIA

LOU-2
K_u-BAND PERMANENT MAGNET FOCUSED BACKWARD-WAVE OSCILLATOR

⑪

LOU-2 K_u-BAND PERMANENT MAGNET FOCUSED BACKWARD-WAVE OSCILLATOR

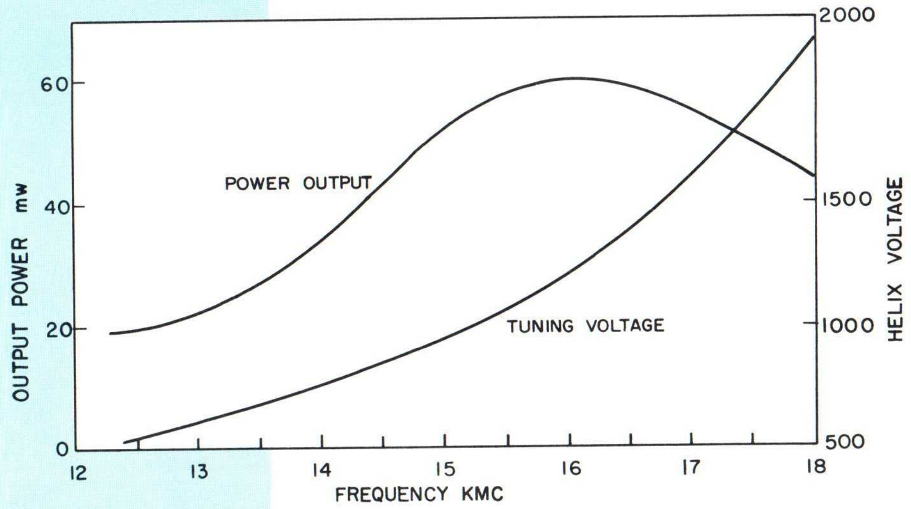
The LOU-2 K_u-band backward wave oscillator, electronically tunable over a frequency range of 12 to 18 kMc, is an ideal signal source for microwave signal generators, panoramic receivers and spectrum analyzers, frequency scan and navigational radars, microwave relay links, and countermeasures equipment. Power output over this wide frequency range is 10 to 60 milliwatts and the signal-to-noise ratio is extremely high. Focused by a permanent magnet, the LOU-2 is housed in a light, compact package which provides protection for the permanent magnet against demagnetizing and allows the tubes to be stored adjacent to one another. The uniform permanent magnet provides a stable focusing field over a wide temperature range. In addition it acts as a heat-sink for the tube so that no cooling is required.

Currently in limited production, these tubes show promise of long life.

LOU-2B IN LIGHTWEIGHT ENCLOSURE

LOU-2 IN PROTECTIVE ENCLOSURE

TYPICAL R-F PERFORMANCE OF LOU-2



- **10 TO 60 MILLIWATTS OUTPUT POWER**
- **12 TO 18 KMC TUNING RANGE**
- **PERMANENT MAGNET FOCUSING**

POWER OUTPUT	10 - 60 mw
FREQUENCY RANGE	12 - 18 kMc
TUNING VOLTAGE	500 - 1900 v
ANODE 1 VOLTAGE	200 v
MAXIMUM VOLTAGE	1900 v
TOTAL CATHODE CURRENT	8 ma
HEATER VOLTAGE	6.3 v

HEATER CURRENT	0.6 amp
R-F CONNECTORS	RG-91/U waveguide with UG-541/U flange
WEIGHT OF TUBE AND MAGNET	11.5 lbs
OVER-ALL DIMENSIONS	5'' height, 5.5'' width, 10'' length

Inquiries should be directed to:

ELECTRON TUBE DIVISION

HUGHES PRODUCTS

LOS ANGELES 45, CALIFORNIA

HUGHES

HUGHES AIRCRAFT COMPANY

MICROWAVE TUBE DIVISION

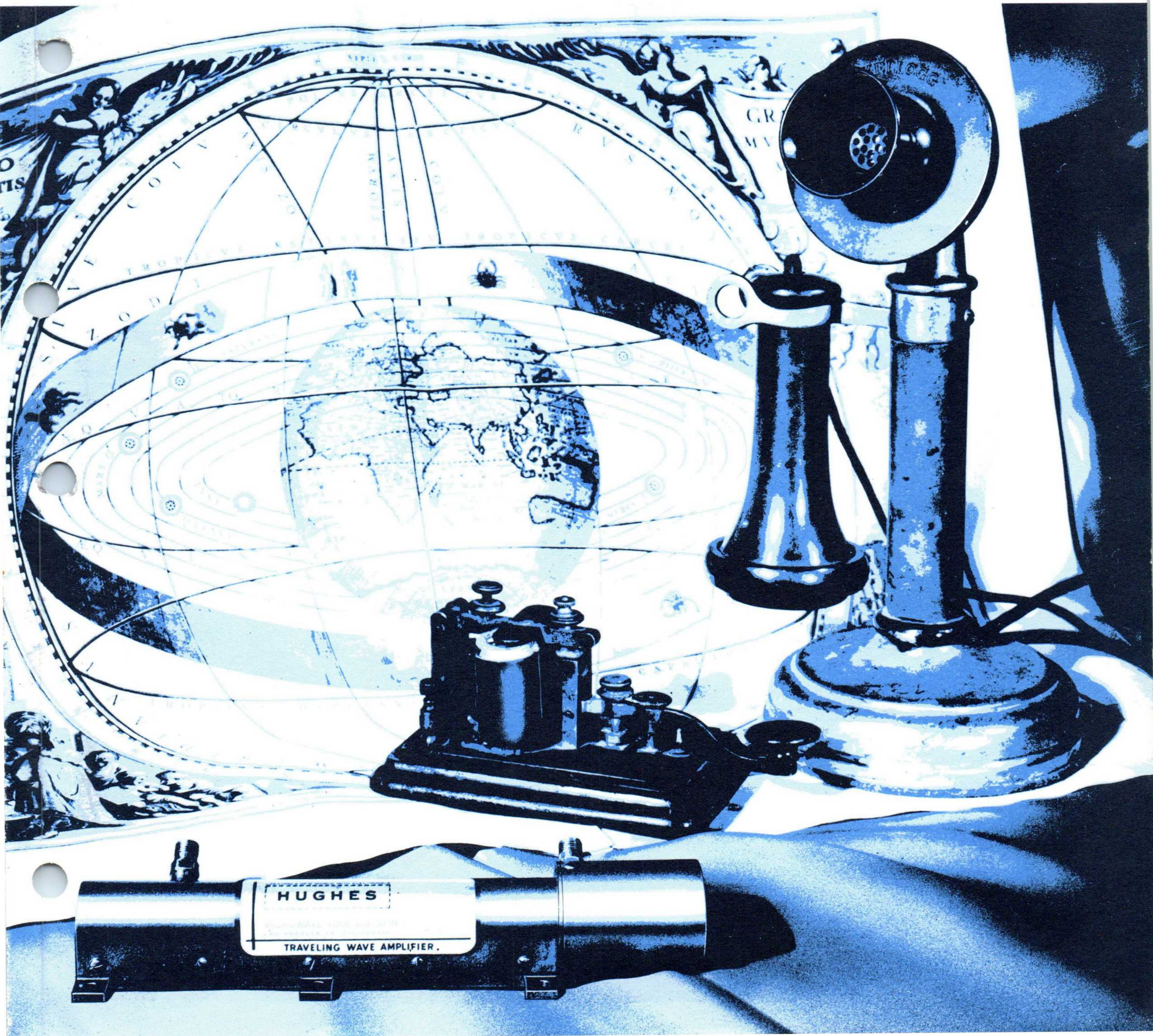
S-BAND

Lightweight TWT Amplifiers

FOR SPACE, MISSILE AND AIRBORNE APPLICATIONS

MODEL 314H—2.5 WATTS

MODEL 349H—10 WATTS

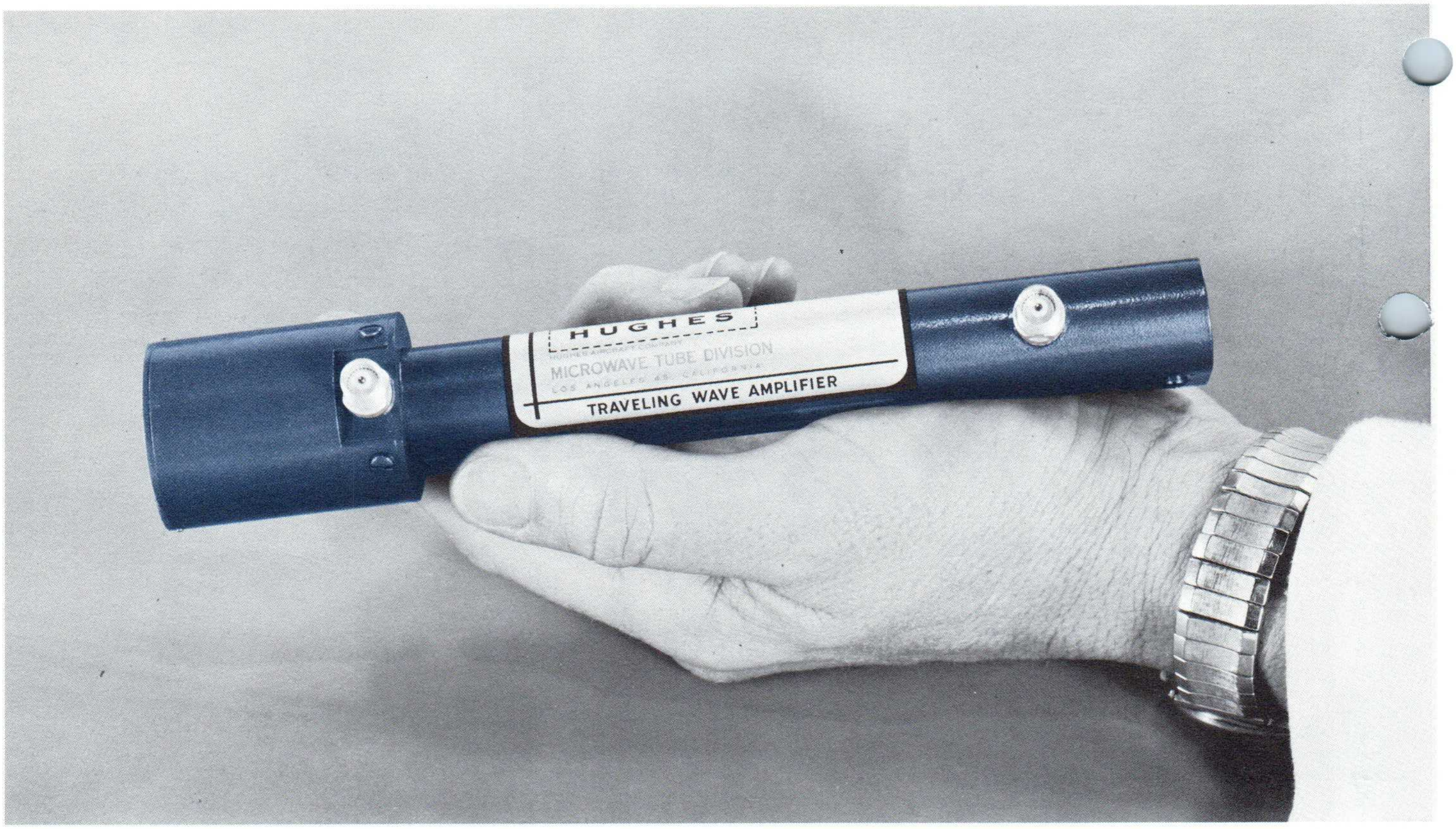


FEATURES

MODEL 314H 2.5 Watts • 1.5-3.0 kMc **MODEL 349H** 10 Watts • 1.8-3.2 kMc

The system designer's need for an extremely lightweight compact TWT is now fulfilled by the introduction into volume manufacture of two new amplifiers featuring:

- ENVIRONMENTAL RUGGEDNESS
- HIGH EFFICIENCY
- LONG LIFE
- HIGH RELIABILITY
- VERSATILITY

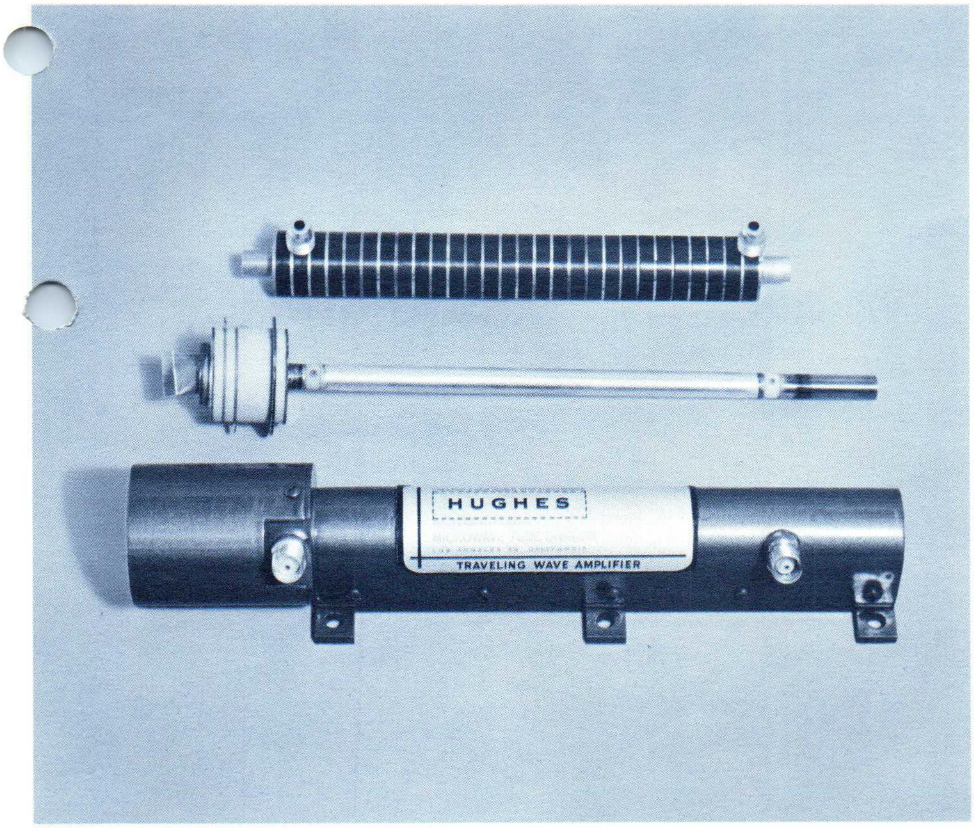


Complete TWT packaged for space. In this configuration the tube can be bolted to the space frame with all cooling provided by direct conduction.

DESCRIPTION

LIGHTWEIGHT Weighing only 12 ounces completely packaged with PPM focusing structure, these tubes have been specifically designed for space and airborne use. Total tube weight excluding reinforced mounting brackets and heat sink is only 8½ ounces.

ENVIRONMENTAL RUGGEDNESS Metal-ceramic construction is used throughout so that maximum reliability and shock resistance are assured. The integrity of this construction has been proven in the environmental chamber under extremely high vibration and shock levels. In addition to extreme shock and vibration resistance capability, the tubes are able to operate over a wide temperature range since no temperature-sensitive materials are used.



TWT separated from space package. At center is the basic vacuum tube illustrating the rugged tal-ceramic construction. At top the PPM focusing magnets and r-f coupler assemblies are shown.

HIGH EFFICIENCY High over-all efficiency is attained by use of a depressed collector and a thermally efficient heater-cathode design. With a maximum efficiency of 30% and a heater drain of only 1.5 watts, power supply requirements have been reduced beyond any comparable device at these frequencies. The low voltage of operation is a further attraction which simplifies the over-all system.

LONG LIFE AND RELIABILITY All known techniques for obtaining very long life, namely, low cathode current density and ion trapping are incorporated in these tubes. Pressurized ultra-clean room facilities for assembly and processing are used to eliminate statistical failures due to uncontrolled quality variations. A large scale life test and reliability program is in progress directed toward insuring very long tube life, typically 20,000 to 40,000 hours, and ultra reliability.

VERSATILITY Although these tubes have been specifically designed to satisfy the most demanding space application, the basic tube design lends itself without change to economical quantity production for any ground, airborne or instrument application. For communications, telemetry, and missile electronics the broad-band high-gain features make possible exciting new system concepts. Of particular interest to the systems designer is the fact that simple changes in the tube design can be made to further optimize certain operating characteristics for any particular application. For example, the gain can be significantly increased by merely extending the length of the amplifying portion of the tube. The center frequencies can be re-aligned anywhere in the S-band spectrum without greatly affecting the package size.

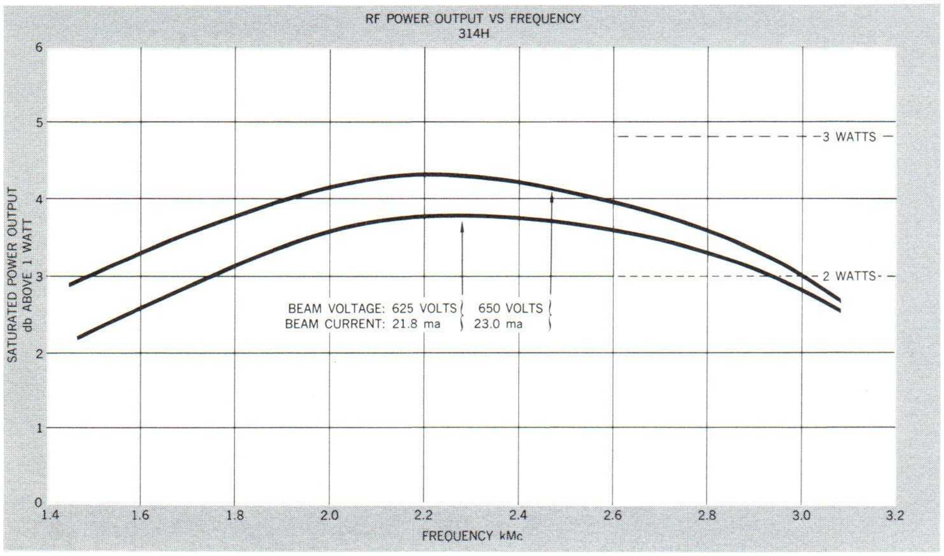
POWER OUTPUT

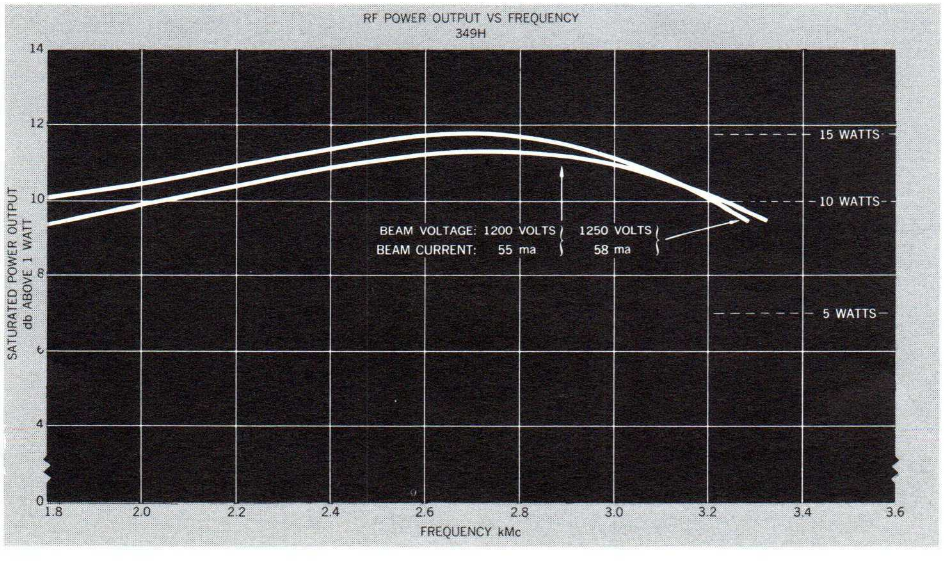
An octave of bandwidth is provided by both the 314H and 349H with NO TUNING OR ADJUSTMENT OF VOLTAGES AND CURRENTS. Broadband capability is characteristic of the helix circuit employed and the special coaxial pin-type r-f connections are particularly well suited to give a very low VSWR over the entire operating band.

The 314H yields in excess of 2 watts; the 349H delivers 10 watts. Significantly, both tubes fit into the same size package and mechanically are virtually identical. Each device can be operated over a limited range of beam voltages and thereby modest adjustments of saturation power output can be accommodated, as indicated by the curves which show two typical operating conditions. Also, the beam current can be varied with a separate anode electrode yielding an even greater range of power output.

The center frequency of the two devices are different because of the existing applications for these tubes. However, it is a relatively simple matter to alter the helix design so as to center the 2 to 1 frequency band anywhere in the S-band spectrum without affecting package size.

The conversion efficiency of these devices is quite high over the 2 to 1 frequency band and is not greatly affected by the operating voltages and currents.

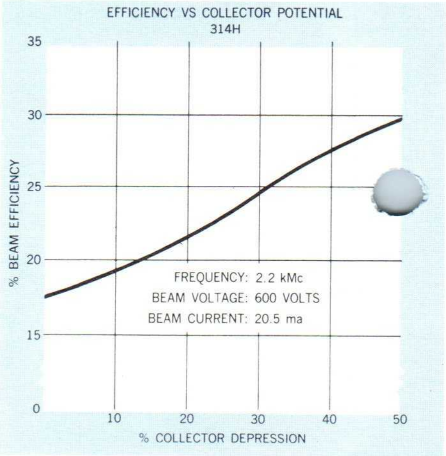

RF POWER OUTPUT VS FREQUENCY
314H


RF POWER OUTPUT VS FREQUENCY
349H

EFFICIENCY

Even though the r-f wave extracts energy from the electron beam, considerable energy remains when the beam enters the collector. If the collector is operated at ground potential as it typically is, the beam energy is dissipated in th[illegible]rm of useless heat. By applying a negative potential to the collector the over-all conversion efficiency is greatly enhanced.

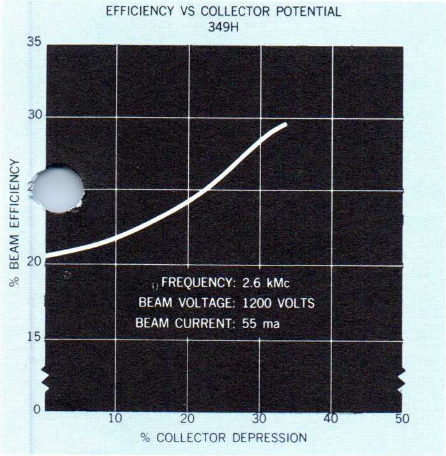
In addition to greatly improving system efficiency, this type of operation significantly reduces the collector cooling requirements. If the over-all conversion efficiency is doubled, collector heating


EFFICIENCY VS COLLECTOR POTENTIAL
314H

is reduced by a factor of two.

Maximum efficiency is achieved when the collector is depressed to 50% of the cathode potential. Beyond this point there is a gradual degradation in efficiency and also there is excessive heating of the helix circuit due to returned electrons impinging on it.

Even for systems in which the power supply circuitry does not permit the recapture of the beam energy the basic beam efficiency is quite high—between 17% and 21%.

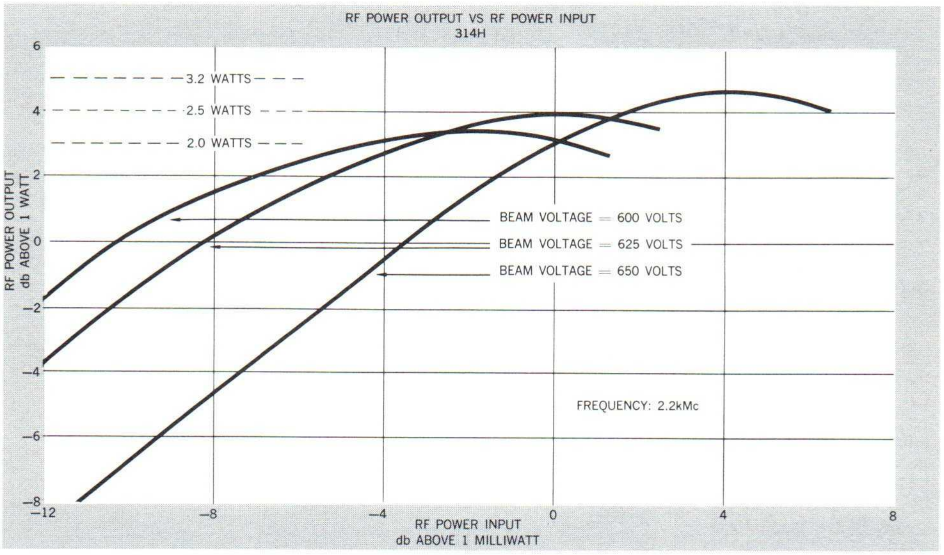


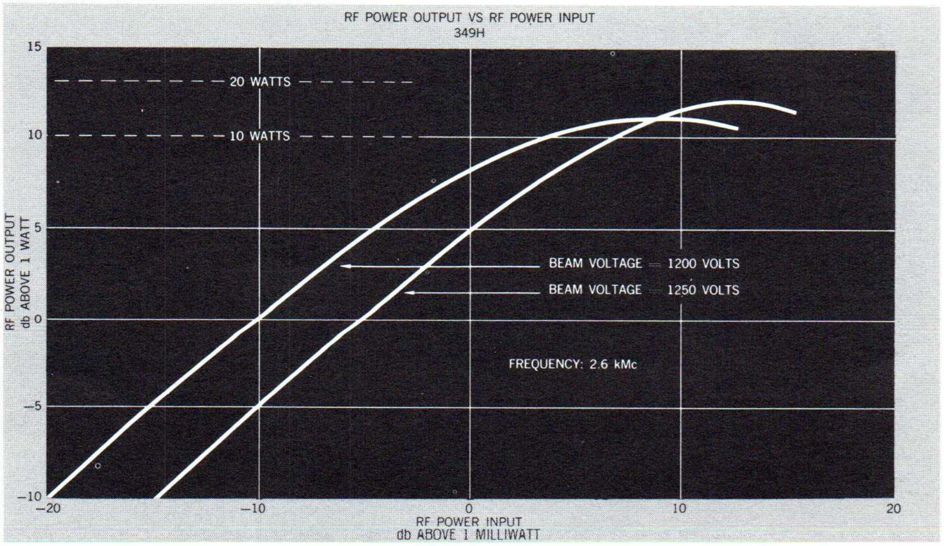
COMPRESSION CURVES

The so called "compression" curves show how the power out varies as a function of r-f drive power. For power outputs 4 db or more below saturation the curves are linear. Above that point the output power levels off and then begins to drop in a fashion characteristic of helix-type TWT's. At saturation the r-f gain is approximately 6 db less than the gain at small signal levels.

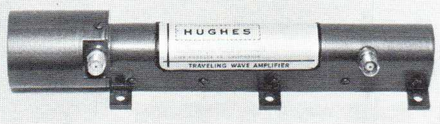
At different beam voltages the saturated power output occurs for different levels of r-f drive power although the maximum power output is not very sensitive to such changes. It should be noted these curves are for one particular frequency and that the numbers will vary somewhat with frequency even though the shape remains fixed.

These curves are quite useful in determining the change in output power for incidental variations in the operating parameters.





ELECTRICAL & MECHANICAL SPECIFICATIONS



314H

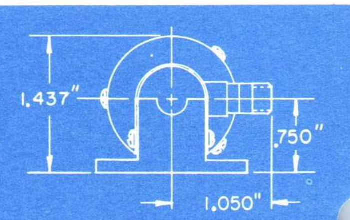
Frequency	1.5 to 3.0 kMc
Power Out	2.0 watts min over frequency band (up to 2.5 watts at midband)
Efficiency (including heater power)	20% min. over frequency band (up to 27% at midband)
Total d.c. power input (including heater power)	10 watts
R-F saturation gain	33 db
Cathode voltage	—650 volts
Collector voltage	—300 volts
Helix voltage	0 (ground) volts
Anode voltage	+60 volts
Heater voltage	5.0 volts
Heater current	.300 amps
Cathode current	20 ma
Anode current	.05 ma
Helix current	5.0 max
Collector current	15 ma
Weight	12 oz.
Predicted Life	40,000 hrs.

349H

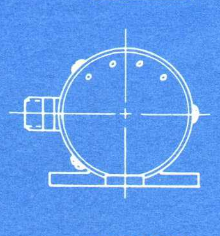
Frequency	1.8 to 3.2 kMc
Power Out	10 watts min. over frequency band (up to 14 watts at midband)
Efficiency (including heater power)	20% min. over freq. band (up to 28% at midband)
Total d.c. power input (including heater power)	50 watts
R-F saturation gain	30 db
Cathode voltage	—1250 volts
Collector voltage	—310 volts
Helix voltage	0 (ground) volts
Anode voltage	+60 volts
Heater voltage	5.4 volts
Heater current	.33 amps
Cathode current	49 ma
Anode current	.1 ma
Helix current	6.0 max.
Collector current	43 ma
Weight	13 oz.
Predicted life	20,000 hrs.

R-F connectors	Type TM Female
Cooling	Conduction through mounting brackets to heat sink
Focusing	Periodic permanent magnet
Construction	Metal ceramic

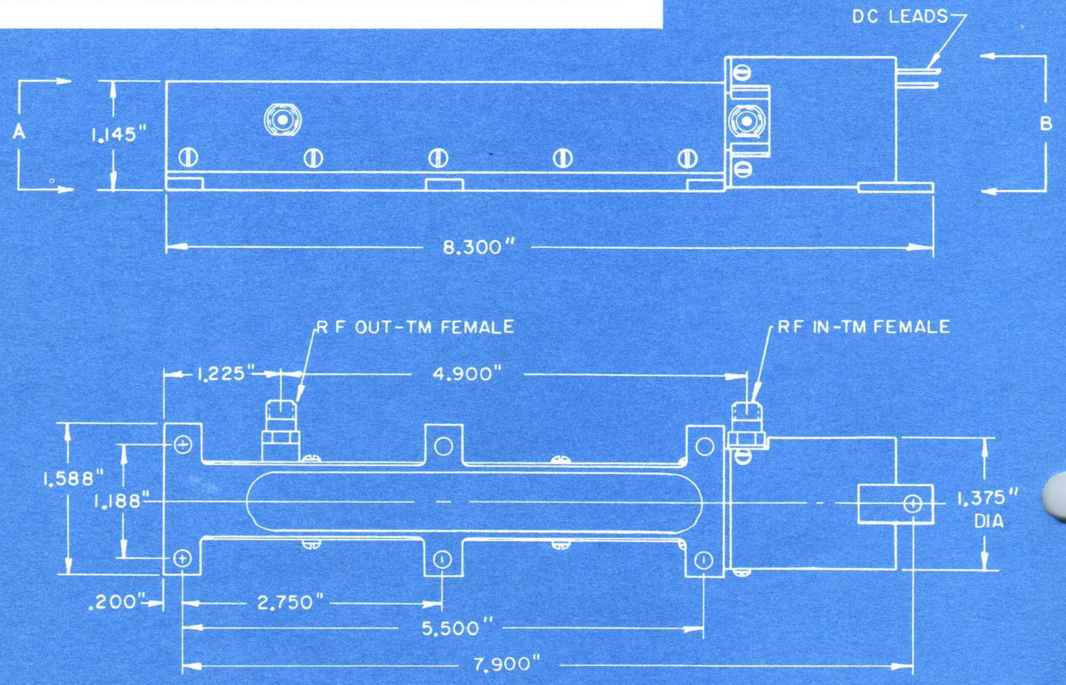
OUTLINE & MOUNTING



VIEW A-A



VIEW B-B



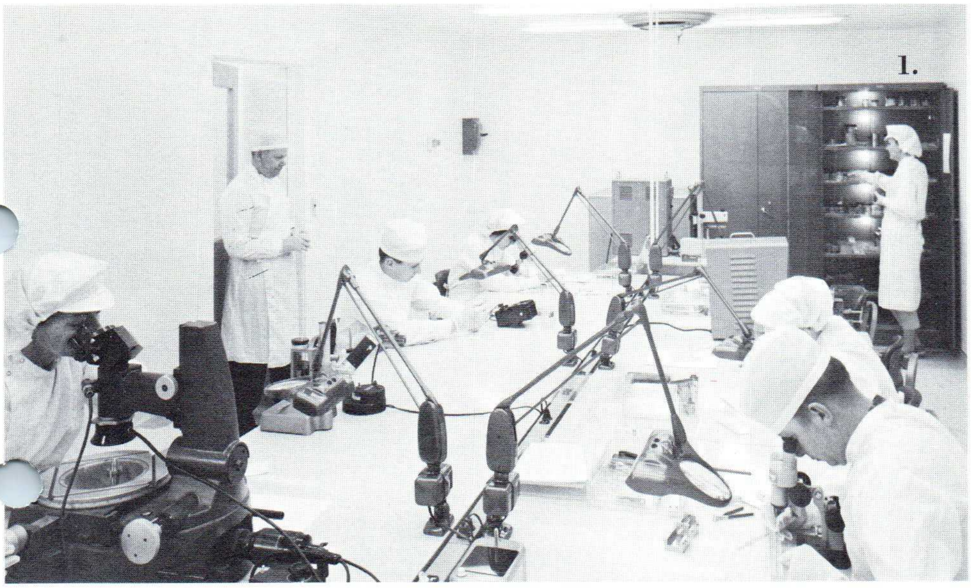
PRODUCTION & RELIABILITY CONTROL FACILITIES

1. CLEAN ROOM An extremely important aspect of the production of reliable electron tubes is the control of dust particles, general cleanliness, and materials preparation. A separate facility has been established exclusively for these TWT's and assembly of all internal parts is performed in dust free, pressurized rooms. Assembly personnel wear special lint free clothing and enter the area through pressure chambers. All parts and subassemblies undergo special treatment and multiple inspections to insure the highest level of confidence. In order to avoid any possible contamination due to lack of control, the processing and testing equipment is never used for other similar type TWT's.

2. BAKEOUT High temperature bakeout of these tubes is done in special vacuum ovens to eliminate all oxidation of the critical seals. The failure rate is significantly reduced by such refined techniques.

3. CONSOLE Complete consoles for life, shock, and vibration tests enable preselection and pre-aging of tubes for critical space applications. Very high levels of reliability can thus be established before tubes are delivered and incorporated in the final system. A continuing program of exhaustive testing assures attainment of predicted life and reliability.

4. TEST In addition to normal electrical specification checking, tubes designated for space are carefully checked for time stability of parameters and for cathode activity as indicated by minimum cathode temperature. Those showing superior characteristics are then placed on aging racks for continuous monitoring of parameter stability and cathode activity.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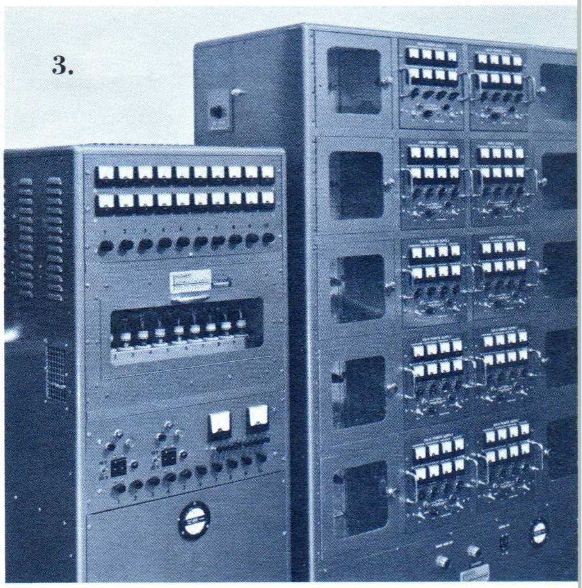
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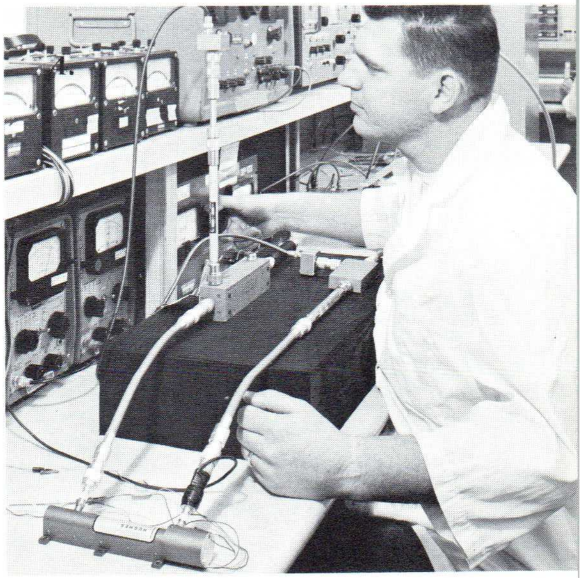
4.

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REGIONAL OFFICES

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MAS-1A

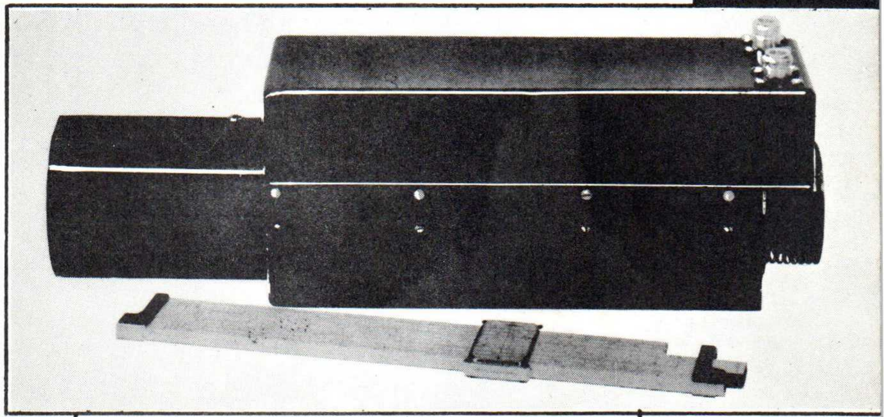
periodically focused traveling-wave amplifier

HUGHES PRODUCTS
MAS-1A
periodically focused
traveling-wave
amplifier

DESCRIPTION

The MAS-1A tube is an S-band periodically focused traveling-wave tube amplifier with power outputs of one kilowatt over a frequency band of 2,000 to 4,000 megacycles. Peak power outputs are obtained with duty cycles up to 0.005 when operated with one watt drive. The tube has a gain of 30 to 33 db, giving an excess of one kilowatt over most of the band.* When two tubes are operated in cascade, the one kilowatt output can be obtained with a drive of only one milliwatt. The type of permanent-magnet focusing field employed in the MAS-1A eliminates the solenoid, solenoid power supplies and solenoid heat dissipation. The MAS-1A incorporates the permanent magnets required for periodic focusing in an all-metal package, thus minimizing external magnetic fields.

**Gain in excess of 27 db is obtained at each band end point, 2,000 to 4,000 megacycles.*



MECHANICAL DESCRIPTION

- Self-contained in all metal package
- Permanent-Magnet, Periodic-Focusing
- Forced Air Cooling
- Weight: 17½ pounds
- Length: 17 inches
- Height: 5½ inches
- Width: 3½ inches
- R-F Connectors
  - Input: Type N
  - Output: Type N
- DC Connectors: Duo Decal 12-pin small shell tube base

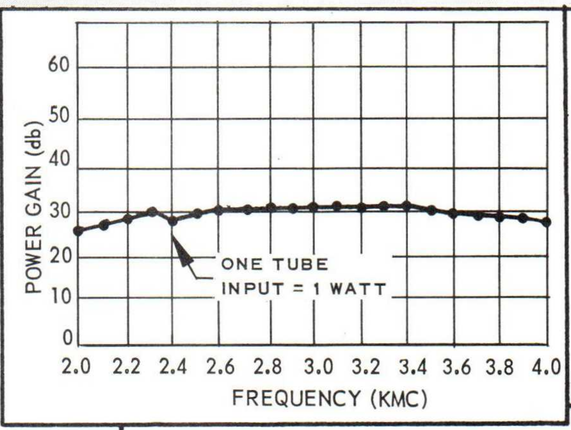
ELECTRICAL CHARACTERISTICS

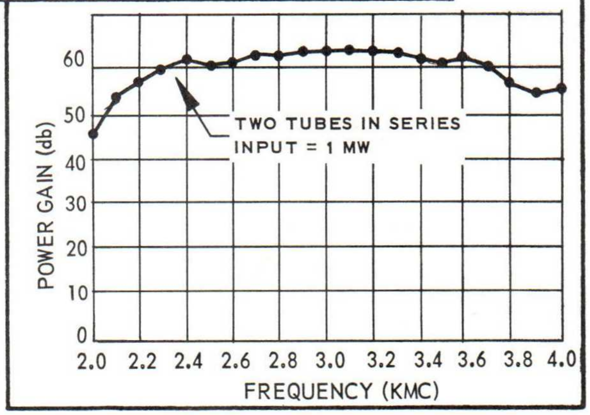
- Frequency Range: 2-4 kmc
- Power Output: 1 KW with 1 watt drive or 1 watt with 1 milliwatt drive
- Gain: Small Signal – 33 db
  Saturation Gain – 30 db

TYPICAL OPERATING CONDITIONS

- Heater Voltage: 8.0 volts
- Heater Current: 4.0 amperes
- Cathode Voltage: – 7.0 KV (negative pulse)
- Cathode Current: 1.4 amperes (peak)
- Anode Voltage: } Ground potential
- Helix Voltage: } Ground potential
- Collector Voltage: } Ground potential
- Duty Cycle: 0.005
- Pulse Length: 5 microseconds

R-F PERFORMANCE OF THE MAS-1A





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15

HUGHES PRODUCTS

ELECTRON TUBE DIVISION

TRAVELING WAVE AMPLIFIERS

BACKWARD WAVE AMPLIFIERS

BACKWARD WAVE OSCILLATORS

[illegible] to Bain + Thompsett ✓

MAS-1D

1 KW S-BAND TRAVELING-WAVE AMPLIFIER

This periodically focused S-band traveling-wave tube produces in excess of 1 kw over an octave frequency band (2.0 - 4.0 kMc) and yet the packaged weight is only 7 lb, including the magnets. The large bandwidth is especially important for countermeasure applications and some of the newer communications systems.

By cascading two of these tubes the 1 kw output is maintained with only 1 mw of drive power. The rugged method of assembly and packaging has yielded excellent performance in severe environments.

SPECIFICATIONS

POWER OUTPUT	1 kw peak 5 w average
POWER INPUT	1 w
FREQUENCY RANGE	2.0 - 4.0 kMc
SATURATION GAIN	30 db
MAXIMUM DUTY CYCLE	0.005
BEAM VOLTAGE	7.0 kv
BEAM CURRENT	1.4 amps
EFFICIENCY	18%
GUN TYPE	convergent flow, Brillouin focusing
CATHODE CAPACITANCE	7 $\mu\mu$f

HEATER POWER	28 w 6.5 v
INSERTION LOSS OF TUBE (BEAM OFF)	55 db minimum
R-F CONNECTORS	type N
WEIGHT OF TUBE AND MAGNET	6.9 lbs
OVER-ALL DIMENSIONS	15″ long x 2¼″ o.d. (excluding connectors)
COOLING REQUIREMENTS	air cooled

A high μ gridded gun for this tube is currently under development.

LOU-2
LOU-2B

K_u-BAND PERMANENT MAGNET FOCUSED BACKWARD-WAVE OSCILLATORS

LOU—2

The LOU-2 K_u-band backward wave oscillator, electronically tunable over a frequency range of 12 to 18 kMc, is an ideal signal source for microwave signal generators, panoramic receivers and spectrum analyzers, frequency scan and navigational radars, microwave relay links, and countermeasures equipment. Power output over this wide frequency range is 10 to 60 milliwatts and the signal-to-noise ratio is extremely high.

Focused by a permanent magnet, the LOU-2 is housed in a light, compact package. The uniform permanent magnet provides a stable focusing field over a wide temperature range. In addition it acts as a heat-sink for the tube so that no cooling is required.

LOU—2B

SPECIFICATIONS (LOU - 2 & LOU - 2B)

POWER OUTPUT	10 - 60 mw
FREQUENCY RANGE	12 - 18 kMc
TUNING VOLTAGE	500 - 1900 v
ANODE 1 VOLTAGE	200 v
MAXIMUM VOLTAGE	1900 v
TOTAL CATHODE CURRENT	8 ma
HEATER VOLTAGE	6.3 v
HEATER CURRENT	0.6 amp

R-F CONNECTORS	RG-91/U waveguide with UG-541/U flange
WEIGHT OF TUBE AND MAGNET	11.5 lbs
OVER-ALL DIMENSIONS	LOU—2 5″ height 5½″ width, 10″ length LOU—2B 6⅛″ height, 3 7/32″ width, 9 9/32″ length

PAS-2B

S-BAND LOW NOISE BACKWARD-WAVE AMPLIFIER

An inherent feature of backward wave amplifiers is a narrow, electronically tunable passband which automatically provides image rejection and good selectivity. The PAS-2B combines this feature with the protection against crystal burn-out which results from a low saturation power level. Extremely low noise figure and high insertion loss are its unique features and provide improved sensitivity, receiver isolation, and anti-jamming performance.

This extremely low-noise voltage-tuned S-band backward wave amplifier represents a new concept in microwave receiver design. It is the latest stage in a continuing development of such tubes for r-f preamplifiers in radar, communications, and search receivers. The noise figures produced, lower than those obtainable with any other traveling-wave tube, are possible because of the significant advance represented by the Hughes low-noise gun.

SPECIFICATIONS

LOW-NOISE TUNING RANGE	2.0 - 4.0 kMc with noise figure under 8.0 db
MINIMUM NOISE FIGURE	less than 4.0 db
GAIN	10 - 25 db for low-noise operation
MIDBAND BANDWIDTH	11 mc at 15 db gain
MIDBAND TUNING RATE	2 mc/v
SATURATION POWER LEVEL	1 mw
INPUT-OUTPUT ISOLATION	greater than 50 db (beam off)
TUNING VOLTAGE	180 - 1150 v
MAXIMUM VOLTAGE	2750 v
HEATER POWER	10 w
MAGNETIC FIELD	1000 gauss (solenoid focused)
RF CONNECTORS	Type TNC

PAX-1

X-BAND LOW NOISE BACKWARD-WAVE AMPLIFIER

The 4.5 db noise figure at X-band of this backward wave amplifier offers attractive possibilities for improving many existing radar and communication receivers. This significant improvement over currently available components is principally due to the Hughes low-noise electron gun which exploits a recent discovery in noise phenomena. Another attraction of this device is its narrow bandwidth which is electronically tunable over the X-band spectrum. This feature provides receiver selectivity, image rejection, and anti-jamming capability. The limiting characteristic and the isolation between the input and output terminals yield excellent protection against crystal burnout.

SPECIFICATIONS

OPTIMUM FREQUENCY	8.5 - 9.5 kMc
NOISE FIGURE	4.5 db minimum, 5 db average
GAIN	greater than 20 db
BANDWIDTH	12 mc ± 2 mc
TUNING RATE	6.0 mc/v
SATURATION POWER OUTPUT	0.2 mw
INPUT-OUTPUT ISOLATION	greater than 50 db
TUNING VOLTAGE	420 - 650 v
MAXIMUM VOLTAGE	1500 v
FILAMENT POWER	6 w
MAGNETIC FIELD	1300 gauss (solenoid focused)
R-F CONNECTORS	RG-52/U waveguide with UG-39/U flange

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Please write for additional information:

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ELECTRON TUBES
International Airport Station
Los Angeles 45, California

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⑩ ~~⑮~~ T.P.D. ⑩

PAS-2 / low noise backward-wave amplifier

HUGHES PRODUCTS
PAS-2 /
low noise
backward-wave
amplifier

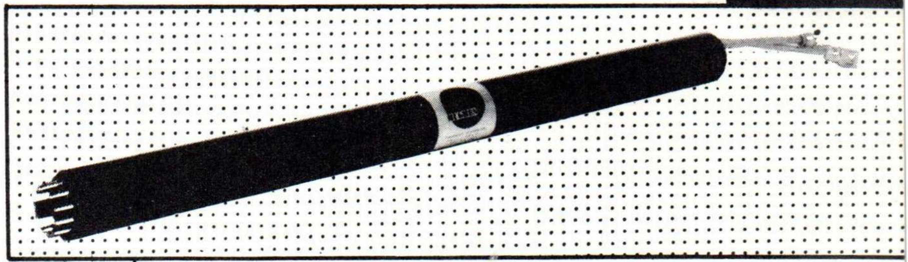
DESCRIPTION

The Hughes PAS-2 Backward Wave Amplifier is a narrow-band, voltage tuned amplifier which accepts and amplifies signals in a specific narrow-band of interest. For example, rapid tuning of the pass-band is accomplished by adjusting a single voltage.

Specifically, the PAS-2 is designed for use as an r-f preamplifier stage in radar communications, and other microwave receivers with vastly improved sensitivity and flexibility.

The PAS-2 features:

- Frequency Range 2400-3500 Mc
- Insertion Noise Figures of the order of 4-½ db.
- Tube Noise Figures of 4 db and lower
- Voltage-fused TRF Capability
- Crystal Protection
- Elimination of Spurious Input Signals
- Cold Isolation greater than 80 db
- Rejection of Image Response

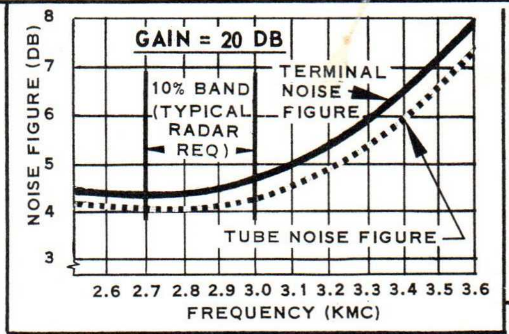


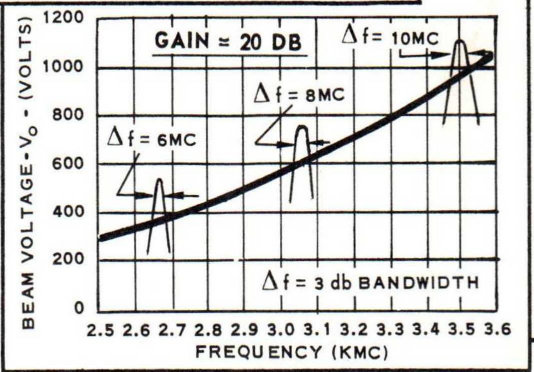
MECHANICAL DESCRIPTION

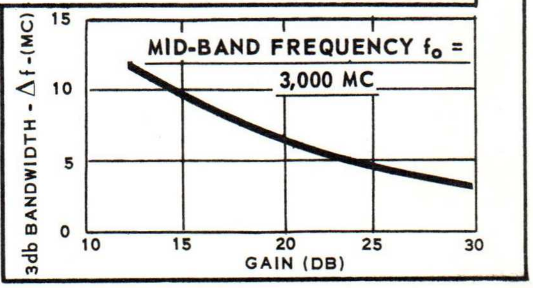
Overall Capsule Length	22 inches
Capsule Diameter	1.5 inches
Base	11 pins (1-1/6" pin circle) (Utilizes Amphenol 49-SS116 tube socket or equivalent)
R-F Connectors:	
Input	Type TNC
Output	Type TNC
Weight	3 lbs.

TYPICAL OPERATING CONDITIONS (NOM. at 3000 vc)

Heater	6.3 volts 1.3 amps	
Operating Potentials (DC)		
Helices	0 volts (reference)	
Collector	1500 volts	
Cathode	-540 volts	
Anode No. 1	3 volts	with respect to cathode
Anode No. 2	30 volts	
Anode No. 3	60 volts	
Anode No. 4	150 volts	
Anode No. 5	150 volts	
D-C Collector Current	0.9 ua	
Current to all other electrodes	2 μ amps max.	
Noise Figure:		
Measured at Capsule Input	4.5 db	
Referred to tube	3.8 - 4.0 db	
Power Gain	20 db	
3-db Bandwidth	8 Mc	
Magnetic Field*	1000 gauss	







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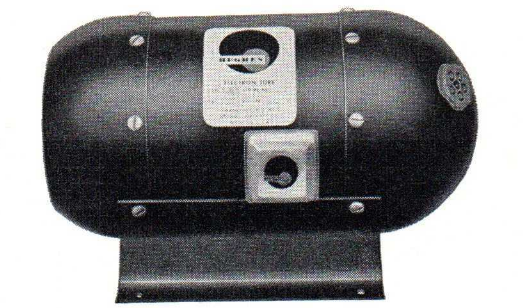
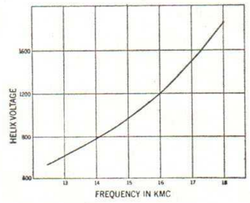
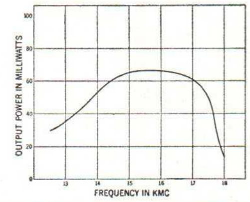
316H

K_U-BAND BACKWARD-WAVE OSCILLATOR. Electronically tunable over a frequency range of 12.4 to 18 kMc. Power output: 30-70 mw over a wide frequency range. High signal-to-noise ratio. Working temperature −55° to +90°C. Tubes are in the field with over 5000 hours' life. Formerly Model LOU-2C.

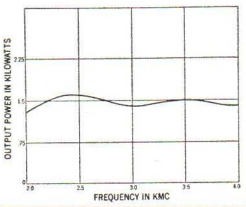


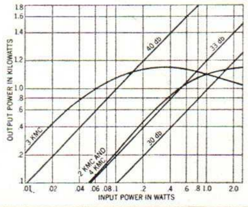




311H

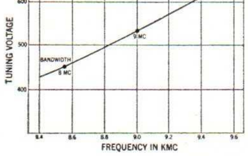
S-band gridded FWA, PPM focused. 1 kw peak .01 duty. 2-4 kMc, 33 db gain. wt. 13 lbs. Formerly Model MAS-1E.

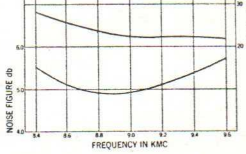




324H

X-band BWA, less than 5.5 db noise figure, 20 db gain. 10 mc bandwidth. Electronically tunable over 8.5 to 9.5 kMc. Formerly Model PAX-1.





Industrial Engineering Notes

(Continued from page 104A)

equipment will cost about $250,000, Convair estimated.

Electronic components and other materials will be bombarded with concentrated electron or ion beams. Studies will also be made of ionized gases under bombardment, simulated upper atmosphere phenomena and neutron and gamma radiation damage.

A new program to minimize radio interference between military electronic equipments and systems was announced by the Department of Defense.

The "Radio Frequency Compatibility Program" is aimed particularly at insuring that electronic systems possess capabilities for rejecting interference and operating at intended levels of efficiency without degradation caused by unintentional interference. Guidelines have been set up for new engineering standards, measuring and testing techniques, analysis procedures and frequency allocation methods.

In the research and development area, new radar standards will reflect the need for different values for different functions, such as airborne surveillance, missile control or shipboard height-finding. Standards for communications, navigational aids, telemetering and other equipments will be improved or developed to insure that interference characteristics are shown. Joint standards will also be established for instrumentation, measurement techniques, test procedures and data reduction.

"Equipment spectrum signatures" will be required on specifications at all levels of development of existing and new radar equipments. DOD defines a spectrum signature as a summary of data showing all radio frequency energy radiations of electronic equipments. It also gives the characteristics of receivers influenced by electromagnetic energy.

A push-button electronic scouting system was unveiled by the Army as "the greatest single advance in the art of surveillance since the days of the Army frontier scout."

The system will make it possible for battlefield commanders, for the first time, to learn instantly—without risking a single soldier—what is going on in enemy territory.

"The system being developed combines jet speed with the lighting speed of electronics," the Army said. "It consists of advanced ground and airborne equipment and an unmanned, jet-powered combat surveillance drone which sends back information while in flight."

The statement added that the system will function day or night, under all weather conditions, and will not be fooled by camouflage. The turbo-jet drone, flying at low altitudes and at high speeds, cannot be stopped easily by enemy action, can remain over enemy territory for extended periods, and may be recovered and refused.

Designated the AN/USD-5, the system

(Continued on page 110A)

~~19~~ 20 T.P.D.

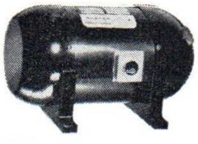
HUGHES LINE OF K_u-BAND BWO's

Hughes K_u-band backward-wave oscillators are all permanent-magnet tubes with the compact, lightweight Hughes design that has proved so reliable. They are ideally suited for use in microwave signal and sweep generators, panoramic receivers, spectrum analyzers, frequency scan and navigational radars and countermeasures equipment. They feature low spurious output and narrow spectrum width. They are designed to give you thousands of hours of trouble-free life.

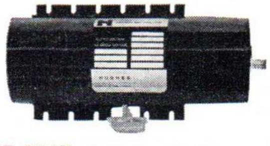
The new 326H, shown here, is of particular interest. It is specifically designed for use in test equipment and other strictly commercial instrumentation—and priced for that market. It is a small, streamlined tube with excellent operating characteristics.

All the tubes shown here are production products. Hughes will ship to meet your immediate requirements. For prices and full particulars, write today to Hughes Microwave Tube Division, 11105 Anza Avenue, Los Angeles 45, California.

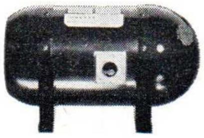
THE 326H For commercial applications. Minimum output: 10 mw over 12.4 to 18 kmc band with power rising to 65 mw in the center of the band. Like all Hughes BWO's, the Hughes 326H requires no external cooling. All electrodes are isolated from each other and from the case.



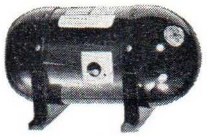
THE 315H Covers the entire K_u band. Average power: 50 mw. Frequency range: 15.8-17.2 kmc. Total weight of tube and magnet: 11.5 lbs.



THE 316H Full band. Average power: 10-60 mw. Frequency range: 12.4-18.0 kmc. Total weight of tube and magnet: 11.5 lbs.



THE 317H Average power: 60 mw. Frequency range: 13.5-15.5 kmc. Total wt., tube and magnet: 10 lbs.



THE 318H Average power: 30 mw. Frequency range: 17.5-19.5 kmc. Total wt., tube and magnet: 10 lbs.

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MICROWAVE TUBE DIVISION

IRE People

(Continued from page 82A)

member of the Montclair Society of Engineers and a former president of the New Jersey chapter of the National Industrial Advertisers Association. He presently serves as a guest lecturer in sales engineering at the Newark College of Engineering, Newark, N. J.

Professional Group Meetings

ANTENNAS AND PROPAGATION

Los Angeles—September 8

"Subsurface Antennas," R. Ghose, Space Electronics Corp., Glendale, Calif.

ANTENNAS AND PROPAGATION MICROWAVE THEORY AND TECHNIQUES

Columbus—September 27

"World's Largest S-Band Radar Transmitter," T. N. Anderson, FXR Inc., Woodside, N. Y.

Syracuse—September 13

"Biological Effects of Microwave Radiation," H. Meahl, General Electric Co., Schenectady, N. Y.

AUTOMATIC CONTROL

Baltimore—October 21, 1959

"Synthesis and Flight Test of a Ballistic Control System," O. Kasfe, The Martin Co., Baltimore, Md.

Baltimore—November 17, 1959

"Non-Conventional Feedback Control Loop Configurations," J. G. Truxal, Polytechnic Inst. of Brooklyn, Brooklyn, N. Y.

Baltimore—March 22

"On the Analysis of Bi-Stable Controls," B. E. Amsler, Johns Hopkins Univ., Baltimore, Md.

Baltimore—October 5

"Impressions of Russian Progress in Automatic Controls," Dr. J. M. Mozley, Johns Hopkins Hospital, Baltimore; Dr. R. E. Kalman, RIAS Inc., Baltimore, and G. Axelby, Westinghouse Electric, Baltimore.

Baltimore—January 10

"Adaptibility and Ultrastable Systems," N. H. Choksy, Johns Hopkins University.

Baltimore—February 16

"A New Method of Systems Analysis," R. E. Kallman, Martin Co., Baltimore, Md.

Baltimore—April 21

"Random Processes in Automatic Control," C. S. Arelby, Westinghouse Electric Corp., Baltimore, Md.

Los Angeles—September 20

"Moscow Report—Panel Discussion," Dr. J. A. Aseltine, Aerospace Corp.; Dr. A. V. Balakrishnan, A. Rosenbloom, STL; J. M. Salzer, Ramo-Wooldridge, E. L. Peterson, G.E., TEMPO, Santa Barbara.

BIO-MEDICAL ELECTRONICS

Houston—September 13

Election of Officers.

Several possible topics for PG group meetings were discussed, and a program for the coming year is being planned.

Los Angeles—September 22

"Instrumentation Needs in the Clinical Laboratory," G. R. Kingsley, VA Center, Los Angeles, Calif.

"Coulter Red Cell Counter," R. Conklin, Scientific Products, Burbank.

North Carolina—September 23

"Measurement of Heart & Kidney Functions Electronically," Dr. J. Whitley, Bowman Gray School of Medicine, Winston-Salem.

"Visit to USSR," Dr. J. Meredith, Bowman Gray School of Medicine.

The staff of the Medical School conducted tours through the various research

(Continued on page 88A)

18 18 TPR

1 kw Hughes traveling wave tubes in S-Band

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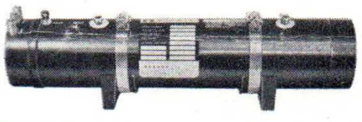
HUGHES

HUGHES AIRCRAFT COMPANY
MICROWAVE TUBE DIVISION

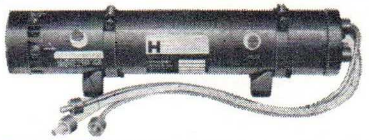
Now available in production quantities, these new and improved tubes offer you 1 kw of pulsed output power, with low power input, minimum heat generation and high reliability.

All these Hughes S-band tubes are lightweight, compact and ruggedly built to withstand the most severe environmental conditions—and provide long life. Each has been fully tested in the field.

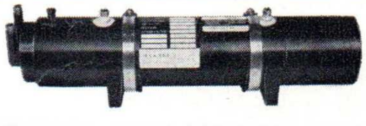
Three of these tubes provide full octave frequency ranges of 2.0 to 4.0 kmc and you have a choice of either ½ or 1% duty, in either ungridded or gridded versions, and with gains up to 37 db. All are permanent magnet periodically focused.



311H Gridded, 1 kw minimum peak power output, 1% duty, 36 db small signal gain @ 50 mw input. Weight: 13 lbs. Length: 17-7/16". Meets usual customer requirements of MIL-E-5400, Class I environmental tests.



312H Gridded 1 kw minimum peak power output, ½% duty, 36 db small signal gain @ 50 mw input. Weight: 11 lbs. Length: 15-3/8". Meets usual customer requirements of MIL-E-5400, Class I environmental tests.



304H Ungridded, 1 kw minimum peak power output, 1% duty, 37 db small signal gain @ 1 mw input. Weight: 12½ lbs. Length: 17-31/32". Meets usual customer requirements of MIL-E-5400, Class I environmental tests.

313H Ungridded, 1 kw minimum peak power output over the center portion of the band, ½% duty, 36 db small signal gain @ 1 mw input. Weight: 17½ lbs. Length: 16-5/8". Meets usual customer requirements of MIL-E-1 environmental tests.

For information wire or write:
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PRESENTS A NEW AND BETTER McLEOD GAGE

The KINNEY McLeod Gage answers the many objections to other gages now in use. Its advanced design compacts superior performance into a rugged, versatile instrument that may be permanently mounted on bracket, tank, panel or pipe or, by affixing demountable legs, used as a portable unit.

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IRE People

(Continued from page 102A)

G. J. Laurent

George J. Laurent (A'47–SM'52) has been named executive vice-president of General Atronics Corporation, according to a recent announcement.

He has served as a Vice-President and Secretary-Treasurer of the research and consulting firm since he figured in its founding a half-decade ago, and is also president of Atronic Products, Inc., a subsidiary of General Atronics Corporation.

At Atronics, which specializes in system analysis and the development of advanced techniques in electronics, he has supervised the design and production engineering of a code recognizer, automatic checkout gear and radar control and presentation equipment.

A 1939 graduate of Massachusetts Institute of Technology, Cambridge, where he received the B.S. and M.S. degrees in Electrical Engineering, he was formerly associated with Philco Corporation, where

(Continued on page 106A)

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307H LEFT: 100 kw peak power output (500 watt average), 8.5—9.5 kmc frequency range, 54 db saturation gain, 1% maximum duty cycle, beam voltage = 38 kv, 21 lbs. total weight of tube and magnet.

308H

Control grid $\mu = 55$. 15 kw peak power output (150 watt average), 8.6—9.9 kmc frequency range, 53 db saturation gain, 1% maximum duty cycle, beam voltage = 24 kv, 14 lbs. total weight of tube and magnet.

319H

20 kw peak power output (200 watt average), 8.4—9.6 kmc frequency range, 54 db saturation gain, 1% maximum duty cycle, beam voltage = 24 kv, 17 lbs. total weight of tube and magnet.

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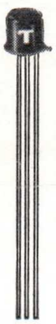

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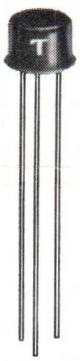

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Two series of diffused silicon PNPN bistable switching devices with very low triggering requirements and micro-second switching.

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Plus **2N1595-2N1599** series with same current and voltage ratings

Series	Package
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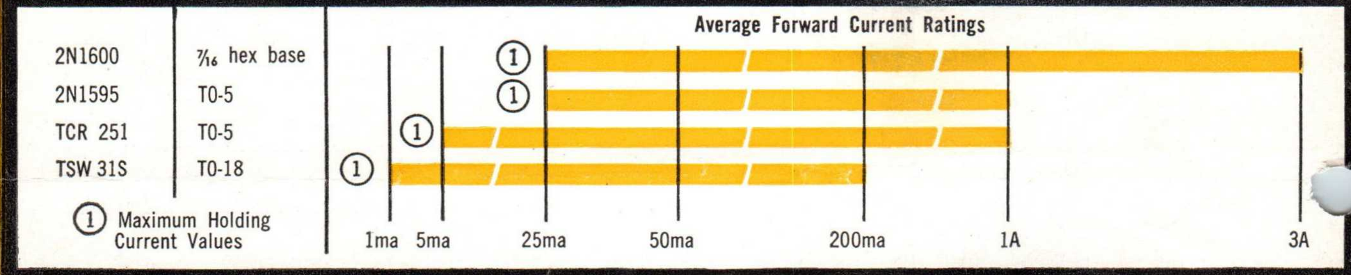
TCR 520	$\frac{11}{16}$ hex base
TCR 510	$\frac{11}{16}$ hex base
TCR 505	$\frac{7}{16}$ hex base



2N1600	$\frac{7}{16}$ hex base
2N1595	TO-5
TCR 251	TO-5
TSW 31S	TO-18

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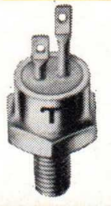

NEW! 2N1600-2N1604 and TCR505-TCR4005 series diffused Silicon Controlled Rectifiers

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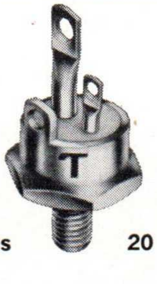
- Voltage ratings: Up to 400 volts
- Package: $\frac{7}{16}$″ hex base



10 Amp Series

- Current ratings: 10 amps @ 25°C case; 5 amps at 100°C case
- Voltage ratings: Up to 400 volts
- Package: $\frac{11}{16}$″ hex base

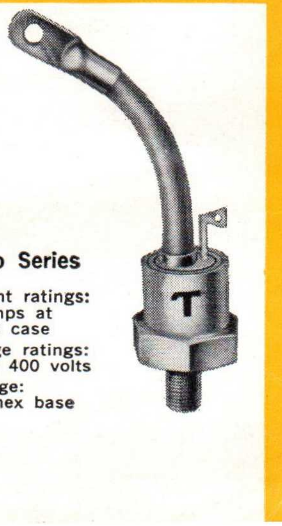
20 Amp Series

- Current ratings: 20 amps @ 25°C case; 10 amps at 100°C case
- Voltage ratings: Up to 400 volts
- Package: $\frac{11}{16}$″ hex base

NEW!

50 Amp Series

- Current ratings: 50 amps at 100°C case
- Voltage ratings: Up to 400 volts
- Package: $1\frac{1}{16}$″ hex base



Progress in TWT Development

By Dr. John T. Mendel

Associate Division Manager Microwave Tube Division
Hughes Aircraft Company, Los Angeles, Calif.

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Progress in TWT Development

Communications satellites and aerospace systems are making increasing use of today's new breed of high-performance, rugged and miniaturized TWT's

By Dr. John T. Mendel
Associate Division Manager
Microwave Tube Division
Hughes Aircraft Co.
Los Angeles, Calif.

At microwave frequencies in the 1 to 20 Watt class, the helix-type traveling-wave tube has no serious competition in terms of efficiency, gain, bandwidth, linearity, noise, size and weight. Other devices may possess advantages in one or more of these areas, but none show the combined attributes of the TWT. That's why almost all satellite transmitters operating today utilize the TWT as an output amplifier. Also, ground terminal designers are looking to the TWT to satisfy their increased bandwidth requirements.

Although characteristics vary with application, TWT's for spacecraft typically generate 2 to 20 Watts of CW power at S, C, and X-band over an instantaneous band of many hundreds of MegaHertz. Figure 1 illustrates a typical 8 watt C-band tube in its finished flight package. Different power levels and different frequency bands cause some changes in the dimensions, but the finished package does not vary significantly from this case over the range typified in existing satellites. Operating voltages are generally less than 2 kV and overall efficiencies in excess of 35% are not uncommon with a depressed collector. The total tube weight, including the focusing structure, is approximately one pound and the size is less than 8 inches long by 1.5 inches in diameter. RF gains of between 40 and 60 dB are easily achieved without appreciable increases in length over that typical of a 30 dB device. Gain per unit length is very high for the helix interaction mechanism. Consequently, the over-all circuit length excluding gun and collector is generally quite short.

The excellent mechanical rigidity and resistance to high levels of shock are inherent in the helix and its supporting members. The helix itself is very lightweight and strong even though it does not contain much mass. The supporting ceramic rods and barrel assembly hold the helix tightly in place with rather high force concentrations in such a manner that vibration does not produce any significant movement of the helix wire. Figure 2 shows a helix and rod assembly just as it is being inserted into the barrel. The barrel is predistorted with a special jig (not shown) so that the oversized helix and rod assembly will be very tightly compressed by the barrel after the jig is removed. This technique is responsible for the unusual rigidity of this structure. The electron gun and other parts of the tube are designed and fabricated utilizing modern metal-ceramic techniques which produce structures which are much stronger than those made with glass.

Solving the Focusing Problem

Focusing the long electron beam of a traveling-wave tube is often the most critical aspect of the entire design. One simple approach is to use a solenoid but the power and weight penalty makes this

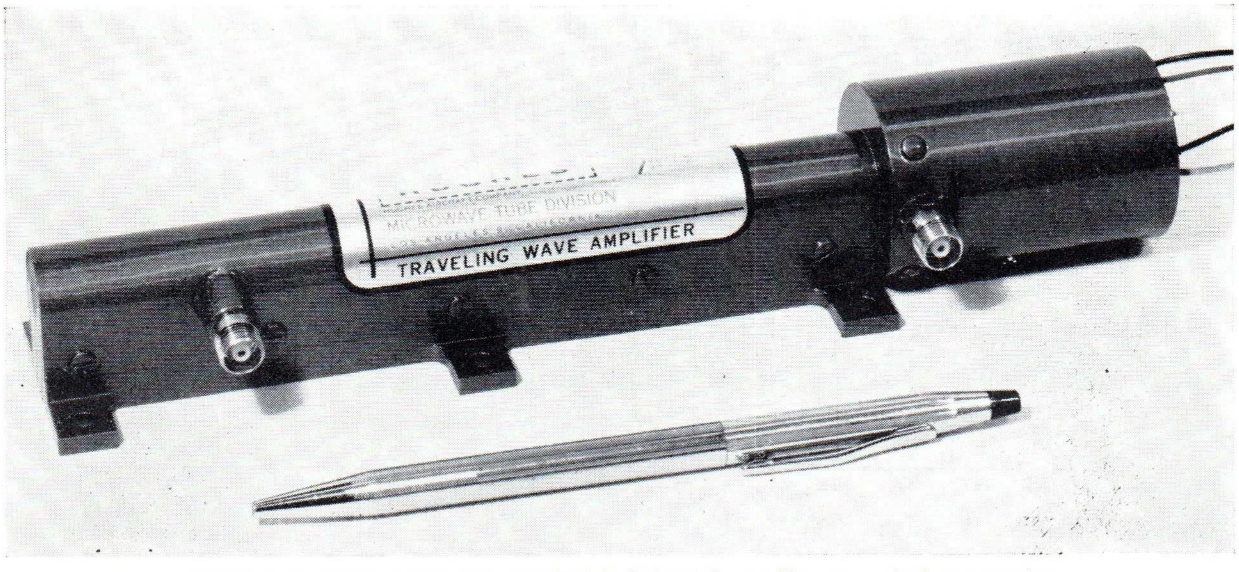

FIGURE 1. An 8-Watt, C-band helix type TWT is designed for satellite communications transmitter

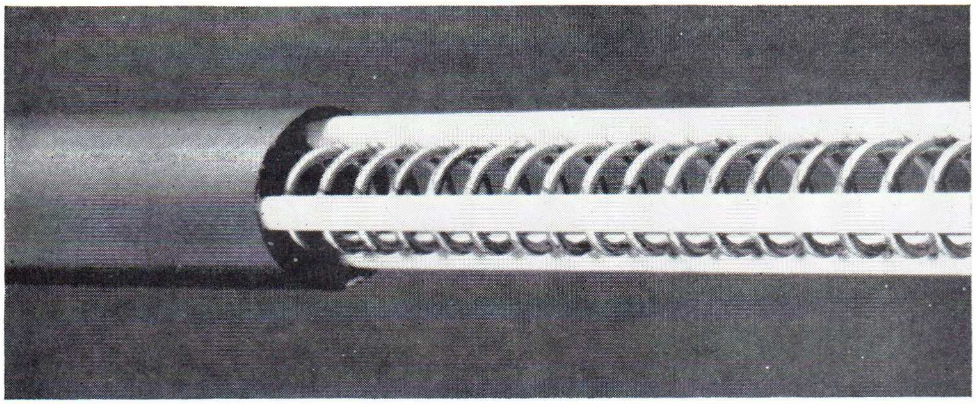

FIGURE 2. Cutaway of conventional helix and ceramic rod assembly as used in typical TWT'S

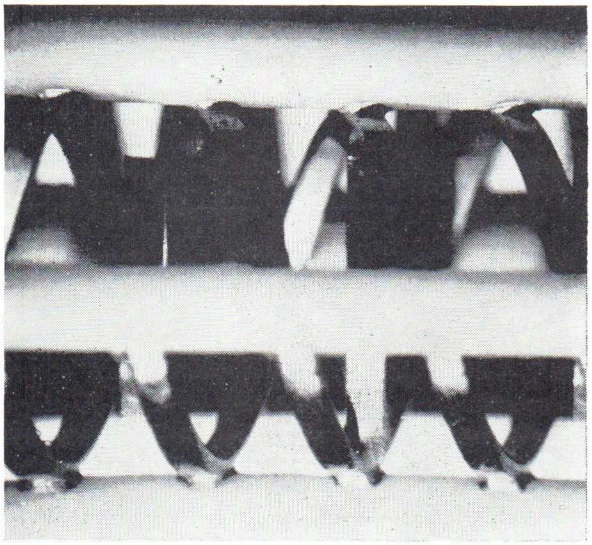

FIGURE 3. Closeup view of C-band helix that has been brazed to beryllium oxide ceramic rod structure

solution unattractive for space applications. Fortunately, PPM focusing has been perfected to the degree that for modest power levels it is as reliable as other forms of magnetic focusing. With the continued development of platinum-cobalt magnets, a magnetic focusing structure has been devised which generally does not increase the over-all package size and adds only 6 or 7 ounces to the total weight. The magnets and the iron pole pieces can be soldered directly to the tube barrel forming a very rugged structure which also possesses good heat capacity for ease of heat removal. Since the focusing mechanism is an integral part of the tube assembly, no changes are likely to occur during installation or operating tests in the equipment.

Although intriguing arguments have been advanced for sophisticated methods of electrostatic focusing, such proposals add little if anything to the TWT's existing characteristics. The magnetic package is so heavy that its complete elimination would reduce the weight by a significant value. The price paid to achieve this saving would be the introduction of a relatively undeveloped focusing system which is seriously limited in terms of beam stiffness, intercepted current, and critical potentials necessary for focusing.

Although the bandwidth requirement for many existing telemetry applications is rather narrow, future communications transmitters and space radars may require bandwidths in excess of 10%. Even now, klystrons at the appropriate power levels cannot meet the requirements. In contrast, TWT's possess a bandwidth capability many times that of the most demanding systems. Only if ECM considerations become of prime importance will the full bandwidth potential of helix-type TWT's be utilized. However, for systems where only a few per cent bandwidths are required, the broadband TWT allows a noncritical mode of operation since its parameters determining frequency response are not altered by temperature changes and other unavoidable environment problems.

Toward Higher Power Levels

To date, the primary emphasis of development work on low power helix-type satellite tubes has been efficiency and reliability. Attainable power levels utilizing existing straightforward techniques are adequate to meet the current requirements of satellite transmitters. Consequently, there has been no real incentive to push for higher powers. However, systems engineers are now seriously considering the optimum approach to an order of magniture increase in power output.

One approach to higher power levels which is proving to be highly attractive is the paralleling of TWT's in the 10 Watt class. As many as 16 have been utilized to feed a phased array antenna with each element excited with one TWT. The ease of power distribution and phase control along with a high degree of redundancy makes this scheme superior to the single high powered tube for certain applications. The advantage of employing low voltage tubes which have been thoroughly demonstrated in long life systems is another very important consideration favoring such a parallel transmitter. Failure modes for high voltage power supplies designed to operate with high voltage TWT's are not well understood nor does much statistical data exist.

Kilowatt CW Helix TWT's

In the area of helix-type TWT's, impressive advances have been made at the 1 to 2 kW CW level in the S and C-band spectrum. Just a short time ago, kilowatt helix tubes were limited to duty cycles of less than 5%. Greatly improved assembly techniques coupled with solenoid focusing have increased this limit by a factor of 20! It is now

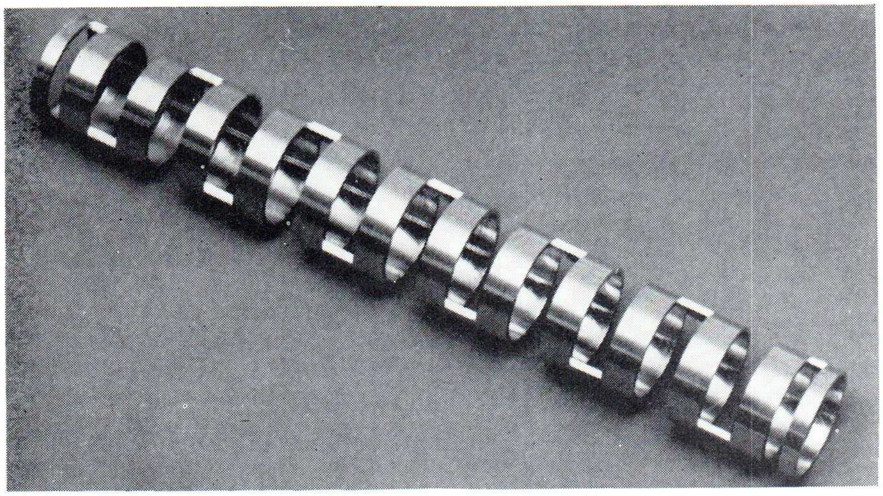

FIGURE 4. Ring-bar combination helix derived circuit is designed for use when peak powers greater than one kilowatt will be encountered

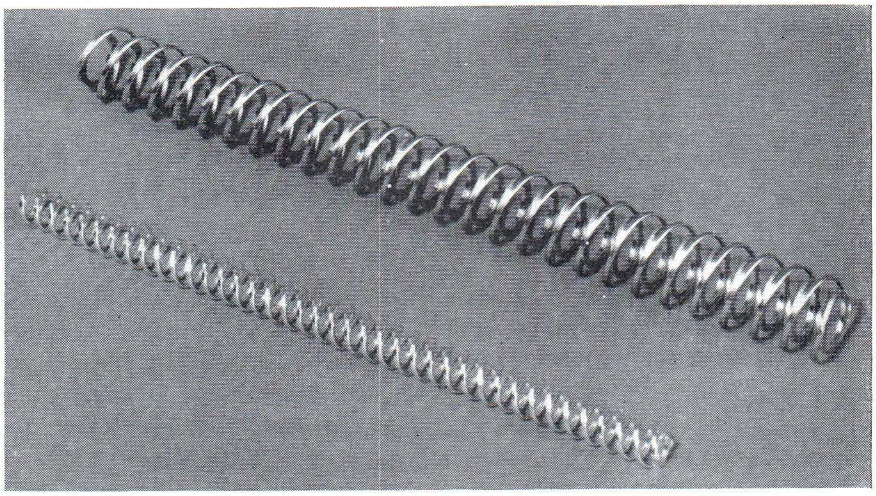

FIGURE 5. Folded-helix circuits at S-band (above) and C-band (below) will handle a maximum of up to 20 kilowatts peak microwave power

possible to uniformly braze a delicate helix circuit to beryllia ceramic.

Figure 3 shows the actual brazed contacts between the helix and ceramic rods. These well-formed fillets must be uniformly maintained over the entire length of helix in order not to disturb the propagation characteristics. The brazed interfaces remove the major sources of thermal impedance and therefore allow the heat to propagate to the outside heat sinks with a minimum of temperature drop. This critical improvement coupled with the excellent focusing attainable with solenoid focusing accounts for the increase of 20 in the power handling capability.

An outstanding example of the efficacy of the helix brazing techniques is the recent demonstration of a 2 kW, CW helix tube operating at 3 GHz. This tube exhibited excellent electrical characteristics over a long period of time, thus proving that these tremendous power densities are indeed practical in a broadband helix-type TWT. Although many experiments have been conducted in the past to show the feasibility of such a high-power tube, this was the first practical device of this sort to successfully generate 2 kW of average power at this frequency. To adapt such a tube to a long-life space vehicle requires considerable refinement in terms of the cooling mechanism and other aspects of the mechanical package. Currently the tube is being developed for an airborne application where 2000 hours of life is adequate.

How Much Power Is Needed?

Initial impressions of the solenoid size and power requirements should be tempered by the consideration of the total power required to operate the TWT. If the high voltage supply is capable of generating 3 to 5 kW of average power, it will completely overshadow the solenoid supply which may be required to deliver only 700 Watts of power. Modern techniques of winding foil-type solenoids directly onto the barrel of the TWT result in a compact focusing assembly which need not cause the weight to increase to impractical values. Since there is a direct relationship between solenoid power and weight, the weight can always be reduced to arbitrarily low values by increasing the solenoid power requirements. Practical cooling considerations, however, limit the range of values which can be selected.

At X-band and Ku-band, the kilowatt class of helix tubes appears to be limited to duty cycles somewhat less than 100%. The structures at these frequencies are too small to safely handle the intercepted beam power coupled with the RF losses.

These are considerable in terms of Watts even though the percentage loss is reasonably low. An even more severe problem is the internal loss which is intentionally designed into the circuit to insure stable amplification.

This loss generally consists of some form of carbon deposited on ceramic rods which in turn are thermally attached to the barrel of the tube. When a sizable reflection occurs at the output of the TWT (for example 2:1 mismatch), hundreds of Watts of power will be dissipated in a very short section of the loss material. If the total volume of the loss is too small, the resulting high temperature will damage the internal parts of the circuit assembly irreversably. At X-band and above, the situation appears to be very precarious in this regard for helix type structures.

Since the helix circuit is inherently capable of yielding good RF performance over an octave of bandwidth, the kilowatt helix tubes possess a bandwidth capability far in excess of the usual radar requirements. It is well known that, in principle, this excess bandwidth could be traded for increased interaction (shorter total length) or improved thermal characteristics. However, very little work has been directed toward such an objective because of the introduction of other completely different filter circuits.

High Peak Power Helix-Derived Circuits

The limitations of the physics of electron optics causes a serious limitation of beam power available at a fixed beam voltage level. This restriction coupled with the propagation characteristics of the helix circuit causes the upper boundary of peak power to be approximately 2 kW regardless of duty cycle. To achieve this power level, the operating voltage must be in the range of 10 kW, which is the practical limit for a conventional helix. Above this voltage value the desired mode of propagation begins to deteriorate in terms of its interaction properties and the device performance is seriously degraded.

To overcome this fundamental limit, a basic change must be effected in the circuit so that higher synchronous voltages may be achieved without affecting the desirable interaction characteristics. Several successful variations of the helix circuit have been developed which permit peak powers in the hundreds of kilowatts even though the average power limitations have not been correspondingly increased. The most common variation is the so-called ring-bar circuit or counter-wound helix.

Figure 4 is a typical ring-bar circuit without any support rods. In the final package, this circuit assembly appears quite similar to that of the conventional helix of Figure 2. It has been utilized in many L, S, C and X-band TWT's ranging in peak powers from 5 kW to 150 kW with average powers as high as 3 kW in the larger structures. Most applications call for bandwidths less than 20% even though the basic capability can be extended well beyond this figure. Although the ring-bar geometry is somewhat more massive than the conventional helix, it still must be supported by ceramic rods inside a round metallic barrel. As a consequence, its thermal capability is not very much greater than the helix, except for the very high peak powers where the over-all length becomes appreciably larger.

Folded-Helix Tube

Another highly successful derivation of the helix TWT is the "folded-helix tube" which utilizes a bifilar helix structure which is loaded with periodic septums. Figure 5 shows two folded-helix circuits covering different frequency bands. Close inspection reveals the presence of the individual septums which impart the unusual propagating characteristics to this circuit. This particular circuit is a more recent innovation which possesses the advantage of being almost as broadband as the unmodified helix. However, it is able to cover the same range of peak powers as the ring-bar circuit and displays somewhat higher interaction efficiencies.

If the bandwidth is not a prerequisite, the circuit can easily be adjusted with simple geometrical changes to achieve excellent characteristics over a narrow band of frequencies. In this sense the circuit has great flexibility and potentially it will perform better than any other existing circuit in this particular class. To date only a few designs exist in the 10 to 20 kW range at S and C-band frequencies and as a consequence specific comparisons are difficult to document. Here again the thermal characteristics are not too far different from the helix or the ring-bar version of the helix.

Below X-band, PPM focusing can easily be applied to both the ring-bar circuit and the folded-helix circuit with some sacrifice in beam transmission when compared with solenoid focusing. Because of the intercepted beam power on the circuit, duty cycles of less than 5% are typical. At X-band, PPM focusing is marginally practical depending on the particular design in terms of power level, voltage and current. Based on simple extrapolations from C-band, it appears that for applications requiring only 10% to 20% bandwidth, PPM focusing is probably quite reasonable. This question of the feasibility of PPM focusing is quite important when these circuits are compared with the more massive filter type high power TWT's which in general are much larger and

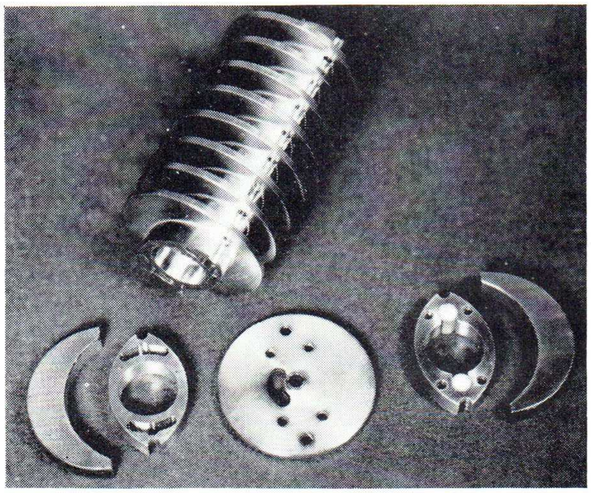

FIGURE 6. Coupled-cavity structure shows periodic permanent magnet focusing lenses that are used in typical PPM TWT's

heavier than their helix counterparts.

Coupled-Cavity TWT's

Perhaps the single most important class of power TWT's for transmitter application is the coupled-cavity filter type TWT. Thousands of these devices have been installed in radar equipment covering a power range from 1 kW to 250 kW and a frequency band extending to millimeter waves. More effort has been directed toward the research, development, and refinement of this particular class of TWT's than all others combined. As a consequence, the existing state of the art is highly advanced, making their application to most radar transmitters a straightforward engineering program.

The basic form of the coupled-cavity circuit is quite similar to a series of klystron-like cavities coupled together by large holes in the cavity walls. The large coupling coefficient causes the highly resonant cavities to behave more like a loaded transmission line than a series of high Q circuits. The wave velocity of the desired propagating mode of the circuit is made synchronous with the electron beam by the appropriate spacing of the cavities; the frequency band is adjusted by the dimensions of an individual cavity just as the klystron frequency is determined. To accommodate different bandwidths, the size of the coupling hole between cavities is enlarged for increased bandwidth and reduced in size for a smaller bandwidth.

In principle, the circuit can be made as narrow as that of a typical klystron with the attendant increase in interaction efficiency. However, such a device may prove to be quite critical with regard to mechanical tolerances because of the critical nature of the individual cavity frequency dependence. At present, highly successful devices have been developed ranging in bandwidths of 2% to 30%, which seems to define the most useful region for this particular circuit.

As is the case with most TWT circuit, the major effort in the development of the coupled-cavity circuit has been concerned with problems of stability. At the edges of the filter network's pass band, propagation characteristics and the interaction mechanism are quite different from those in the desired portion of the band. Frequently, oscillations and large regenerative effects predominate if special precautions are not taken in the basic circuit design. Frequency-sensitive loss which damps out the undesired interaction is often utilized as a method of achieving good stability. Also, the dispersion of the circuit wave must be carefully manipulated to discriminate against the troublesome modes of interaction.

Easily Controllable Tolerances

One of the outstanding aspects of the coupled-cavity circuit is its simple symmetry. Fabrication and assembly of the individual sections can be controlled to almost any desired tolerance even at millimeter-wave frequencies where the parts are extremely small. This advantage allows for quick and easy experimentation to determine the optimum circuit dimensions for a particular requirement. Also, the results are repeatable with few problems concerning the uniformity of the circuit characteristics. In manufacture, such a fundamental trait is naturally quite valuable in lowering cost and increasing reliability.

Prior to the introduction of the coupled-cavity circuit, PPM focusing was thought to be impractical for high-powered TWT's because of the intense magnetic fields required. With the available magnetic materials and with the restrictions imposed by the physics of the electron dynamics, it did not seem possible to design a successful PPM focusing structure for typical high-powered TWT's at S-band frequencies and above. The big breakthrough occurred when it was observed that the magnetic field could be channeled down to the electron beam region by making the cavity walls of iron instead of copper.

Figure 6 is a photograph which illustrates the details of the cavities, magnet walls, and the permanent magnets which are placed outside the vacuum envelope. Here again the circular symmetry of the circuit added considerably to the practicality of the over-all tube design. Each magnetic lens comprising the focusing structure was extended from outside the tube envelope to the small diameter defining the actual beam hole. The enhancement of the magnetic field strength in the region of the electron stream made possible an order of magnitude increase in the beam powers which could be satisfactorily focused. This single innovation more than any other was responsible for the widespread use of high power TWT's in airborne equipments. Prior to this development, weight and size favored other approaches, and the TWT was used only in rare instances.

Direction of Future Effort

The major R&D effort in TWT's will be solely dictated by the immediate requirements of advanced systems. The reason: The enormous costs, both in money and key technical manpower, prohibit exploratory efforts without a very specific goal related to a prime need of economic importance. With this premise in mind, it seems logical that the areas of immediate exploitation will be:

a. High-average-power radar-type TWT's at C-, X- and Ku-band with some increase in activity at mm-waves (35 to 60 GHz) primarily). Emphasis will be to refine present designs for better efficiency, reliability, and reduced size and weight.

b. CW transmitters for ground terminal communications in the 1-to-10-kW class at S-, C- and X-band with emphasis on the commercial C-band region.

c. Broad-band TWT's at all radar frequencies for countermeasure applications.

d. Special-purpose TWT's for satellite vehicles. For the most part, such applications will involve communication or telemetry transmitters, although recent attention has been focused on radar-type systems for space. The primary considerations are efficiency and weight along with reliability. The work in this area involves refining known designs to the point where they would be useful in a space environment. Although the procedures are straightforward, the effort required is considerable and costly.

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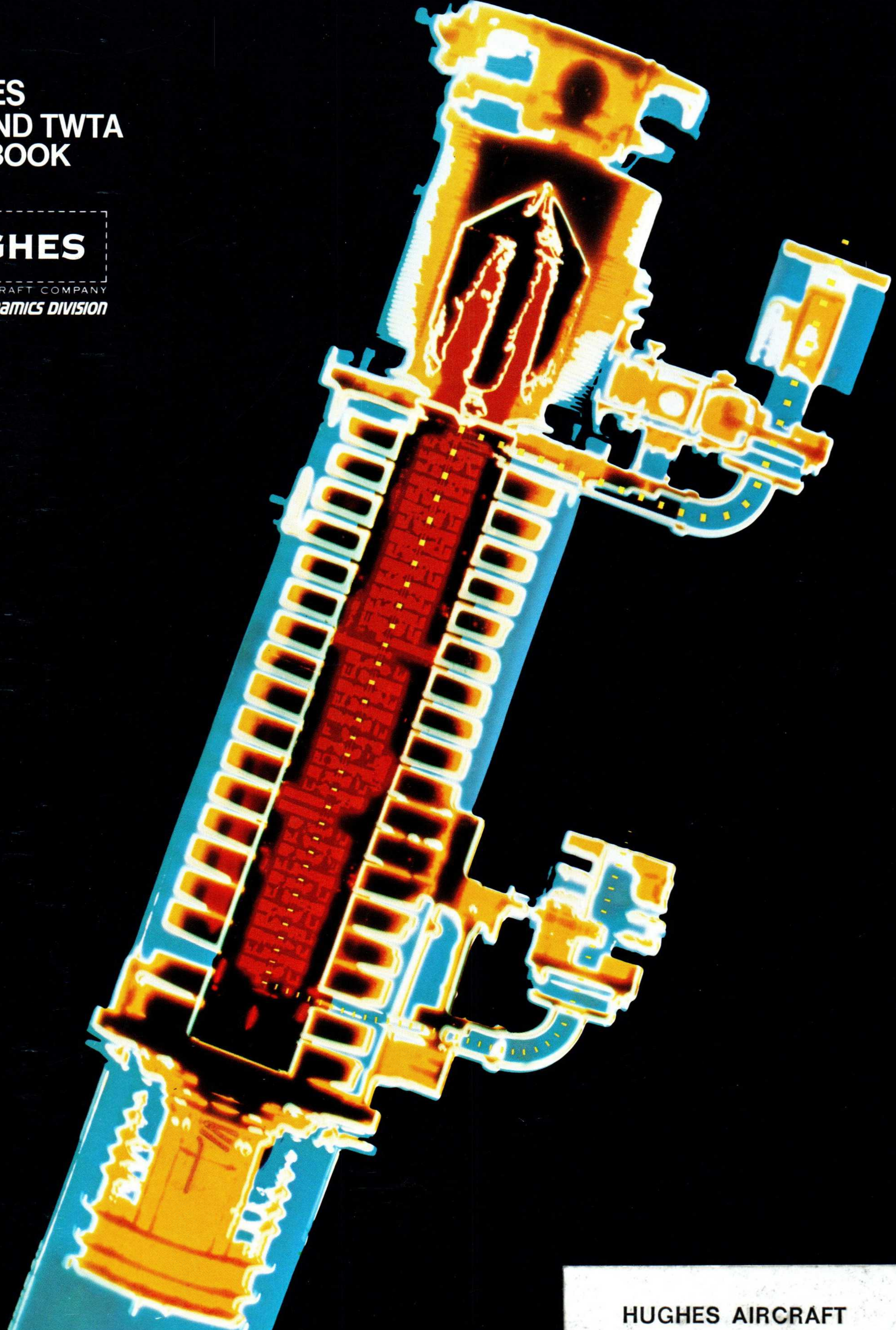

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TWT and TWTA designers handbook

Contents:

Engineering specifications

Radar and ECM TWTs

Communications TWTs and TWTAs

The TWT and Hughes

The traveling-wave tube (TWT), while used extensively only in recent years, is not a new device. Knowledge of its remarkable capabilities, and some of its potential applications, has been known for more than thirty years. It was invented during the latter part of World War II by an Austrian refugee, Rudolf Kompfner, while working on microwave tubes for the British Admiralty.

The TWT was not utilized during the war and remained an experimental laboratory device until the first practical tube was developed by J.R. Pierce and L.M. Field at the Bell Telephone Laboratories (BTL) in 1945 and was detailed in the IRE Transactions in February, 1947. From 1945 to 1950, most of the development work was done at BTL and Stanford University. By present-day standards, these efforts were quite small. BTL was interested in the TWT because of its potential application in the communication field. The military services had other potential applications in mind — radar and electronic countermeasures.

The development of radar during World War II was rapidly followed by the development of countermeasure techniques to deceive and jam them. The evolution of new radars has been partially the result of a continual need to stay ahead of any new countermeasures tactics which might compromise the radar's effectiveness. The trend in search radar has been toward much higher powers and to techniques that will increase visibility while being jammed. A good anti-jamming radar must be able to shift frequency over a wide bandwidth quickly to avoid the jammer's source frequency.

Similarly, the trend in ECM has been toward wide bandwidth system capabilities where the jammer amplifies wideband noise or may deceptively retransmit the hostile radar pulse to offset the radar's ability to determine the target's position. Since wide frequency bandwidths are essential to the employment of such tactics, an amplifying device capable of broad operating ranges with sufficient output power and efficiency was needed. The TWT was found to be ideally suited and the military deserves much credit for funding many of the primary advances in TWT development. Much of this advancement was done at Hughes and the future of the TWT as a key element in many areas was guaranteed.

So, in the late 1950's, a small group of scientists, engineers and skilled technical support people who were involved in TWT R&D throughout Hughes, were brought into one organization. This organization later became the Electron Dynamics Division which has an established reputation as a leader in the development and production of military and commercial TWTs, TWTAs and related subsystems.

Some of the earliest successes for Hughes TWTs were in the area of space applications. Hughes space TWTs and TWTAs have been used in scientific experiments, manned missions, and communication applications by both military and commercial customers. Some of the early programs were Syncom, the ATS series, the Intelsat series and, more recently, in domestic communication satellites both here and abroad. To meet the requirements for future space programs, such as DSCS-III, Intelsat V, Space Shuttle, TDRSS, and the domestic communication satellites, these devices continue to be developed and refined. This work is advancing the state-of-the-art in areas of longer life, lighter weight, higher efficiencies and frequencies, and smaller size.

Other areas where Hughes TWTs are meeting ever demanding customer requirements are in radar, electronic countermeasures, ground terminals and instrumentation applications. In these areas, on-going programs for further product refinement and basic research continue to produce devices and subsystems of the most advanced designs.

The TWT: Still unbeatable for broadband applications

Active ECM systems are designed to receive wideband input radar frequencies and retransmit them with deceptive range and azimuth information or to attempt to jam the source. Such systems must, therefore, perform effectively over a broad range of frequencies, input signal levels and pulse waveforms. The TWT is ideally tailored to such microwave system needs by its inherent ability to provide the largest gain-bandwidth product as compared to any other active microwave component available today.

Other military areas where TWTs are being used include communications, radars, drones and instrumentation. The low-noise capability of the low-power TWT makes it attractive for long-range communications systems where optimum weak signal amplification is critical. Additional benefits offered by the various kinds of TWTs include high-power handling capability, high efficiency and linear increase in phase shift with frequency or constant-time delay.

How the TWT works

The TWT is an electronic amplifying device. It accepts a weak RF input signal and amplifies it many thousands of times. It performs the same function as its principal predecessors—the triode and klyston. It has, however, one characteristic uncommon to other devices—extremely wide bandwidth.

Figure 1 is a simplified sketch of a helix-type TWT structure; the original circuit invented by Rudolf Kompfner. The major elements of a TWT are the electron gun assembly, RF interaction circuit, electron beam focusing magnets, and collector. At the left of the diagram is the electron gun assembly. The gun cathode, when heated, emits a continuous stream of electrons. These electrons are drawn through the anode and are then focused into a tight, narrow beam by a magnetic field and made to travel the length of the tube, eventually to dissipate in the collector in the form of heat. At the same time the cylindrical electron beam is moving along the length of the tube axis, the desired RF signal is fed onto a slow-wave structure, consisting, in this case, of a tightly-wound wire called a helix. The RF energy travels along the helix wire at the velocity of light. However, because of the helical path, the energy progresses along the axial length of the tube at a considerably lower axial velocity that is determined primarily by the pitch and diameter of the helix. The phase velocity of the RF wave, or the speed at which the energy is moving forward, is made synchronous with the velocity of the electron beam. Therefore it is called a "slow wave." The result is that a continuous interaction occurs between the electron beam and the RF signal. This interaction is such that some electrons in the beam are slowed by the RF field, while others are accelerated. As these "velocity-modulated" electrons move down through the helix they form bunches. These bunches, in turn, interact with the helix RF wave and surrender dc energy to it. This results in a great amplification of the RF signal by the time it reaches the output coupler. Single TWTs have been built with power gains of more than 10,000,000 (70 dB).

While the TWT provides extremely high gain, its uniqueness is found in its broadband capability. TWTs have been made to amplify RF signals at frequencies over a 5:1 bandwidth. While not delving into the mechanics of the structure of other tube types, it is important to note that the wide bandwidth provided by the TWT is due to its non-resonant circuit. It is not, therefore, subject to the gain bandwidth equation for other devices, which states that as the gain is increased, bandwidth is decreased and vice versa.

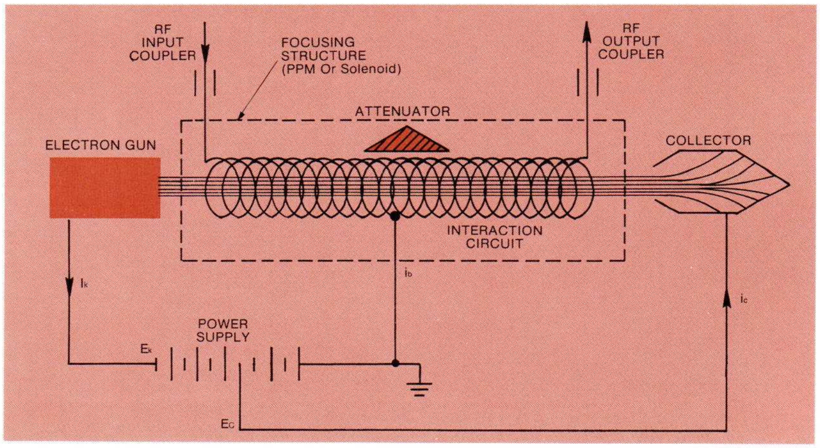
Let's examine the electron gun assembly

The electron gun functions like the lens in a projector—the objective being to get as much electron current flowing into as small a region as possible without distortion. Good gun design is extremely important since it is the source of electrons for the beam. A wide variety of gun designs have been developed by Hughes in an effort to provide better electron beams that are readily adaptable to new TWT types.

Most TWTs are built with control grids to make it possible to turn the electron beam on and off rapidly with a much smaller voltage swing than is required when the cathode voltage is modulated.

The typical grid-controlled gun has six main elements—the gun shell or support structure, which is usually ceramic; the heater; the cathode or electron

Figure 1 The major elements of a TWT are the electron gun assembly, RF interaction circuit, focusing magnets and collector.



emitter; a control grid; a focus electrode to aid in proper formation of the electron beam; and an anode which effectively provides the accelerating field for the electrons. Figure 2 shows a typical gun in cross-section with these various elements labeled.

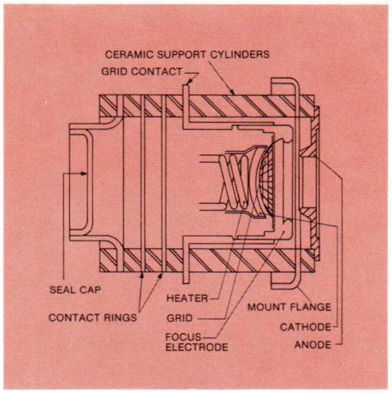
Life and reliability of the end product is largely dependent upon the type of cathode material utilized. Many different types of cathode materials have been used as electron emitters, but two have generally become standard. The first is the oxide type having a nickel base with a barium/strontium coating, and the second, the dispenser cathode. One version of the dispenser cathode has an emitting surface consisting of porous tungsten through which barium is dispensed from the interior which has been impregnated with a mixture of barium-calcium aluminates. A variation of this type of cathode, known as an M-type cathode, is coated with a porous layer of osmium to lower the work function and, therefore, allow a lower operating temperature. A second type of dispenser cathode is the coated particle cathode (CPC) which, as the name suggests, is a structure made up of specially coated particles bonded to a nickel support.

TWT slow-wave circuits

Although there are many types of helix structures, most are based upon Kompfner's original helix design which is still the widest bandwidth structure available. In its basic form, however, the helix design is generally restricted to devices having power outputs of less than 3000 watts.

Figure 3 illustrates the principal component parts of a typical metal-ceramic helix TWT. In the illustration, the metal-ceramic envelope and PPM focusing structure can be seen in the central portion of the photograph. The final assembly, incorporating the balance of the package parts, can be seen in Figure 4. Figure 5 demonstrates the kind of performance characteristics that can be achieved with this type of slow-wave circuit. This extremely broadband performance is ensured by the highly accurate tolerances held during the helix-winding process. This accuracy is essential to the process of interaction between the electron beam and the superimposed RF wave. For example, in a 1,500 volt electron beam, the electrons travel at 1/13th the speed the light. Since the RF signal is carried by the helix at about the speed of light, the resulting linear ratio of the helix to the beam must approximate 13:1.

Figure 2 A typical grid-controlled electron gun includes a support structure, heater, cathode grid, focus electrode and anode.



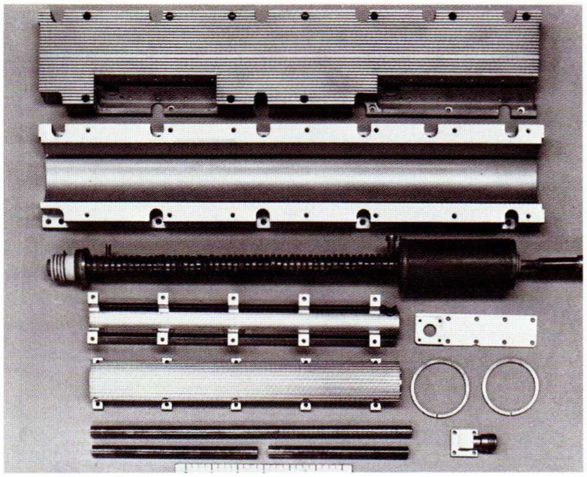
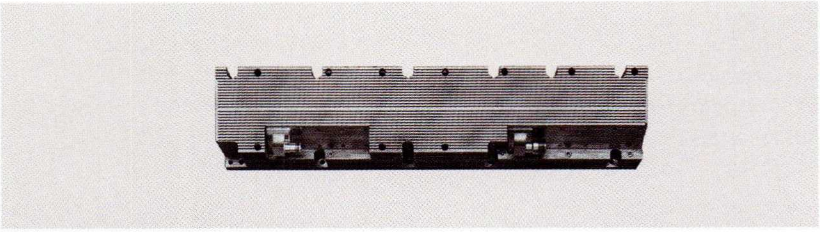


Figure 3 Various components of a typical metal-ceramic helix TWT, with the metal ceramic envelope for the PPM focusing structure shown in the center.

Figure 4 The assembled helix TWT provides broadband pulsed output from 2.5 to 8.0 GHz.



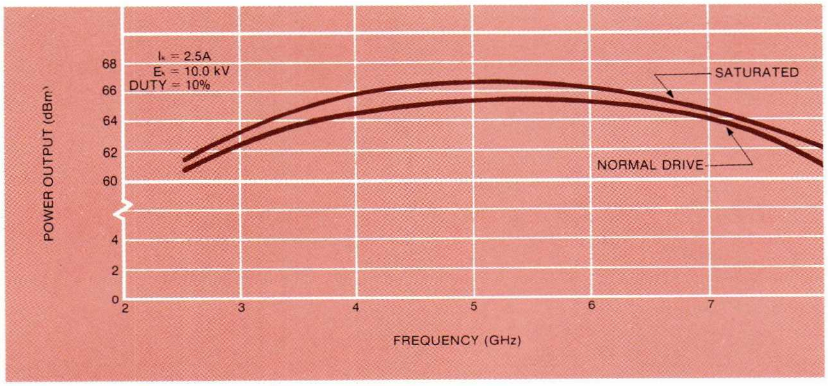


Figure 5 Typical performance characteristics of a metal-ceramic helix TWT.

A number of configurations derived from the basic helix structure have been explored at Hughes in an attempt to extend its properties to provide even higher output powers. Early among these was a scheme of using two helices wound in opposite directions. This device, known as a contra-wound helix, extends the useful range of operating voltages up to the 20 to 70 kV range and allows the use of larger transverse dimensions at a given frequency range. The ring-bar structure shown in Figure 6a, is a version of the contra-wound helix, while Figure 6b, illustrates the classical (bifilar) helix structure.

The peak-power capability of helix tubes is usually restricted to about 3 kW peak output power. The reason for this is that circuit characteristics of helix tubes are susceptible to "backward-wave" oscillations when their operating voltage exceeds 10 kV. Ring-bar tubes with different circuit properties, on the other hand, are not subjected to these backward-wave oscillations and are generally designed for voltages in the 12 kV to 30 kV range with peak-power levels in order of 10 kW to 20 kW. With sufficiently high voltages, peak-power output levels can be in excess of 100 kW.

The interaction impedance of ring-bar structures is nearly twice that of a comparable helix circuit. Consequently, ring-bar tubes generally have higher gain per wavelength (i.e., a shorter tube) and operate with higher efficiency by a factor of approximately 1.2 to 1.3.

The thermal capability of a ring-bar tube can be expected to be significantly higher than that of a comparable helix tube. There are two reasons. First is that the ring-bar structure has twice as many thermal contacts per wavelength for heat transfer than a comparable helix structure. The other is the heavier thermal structure associated with a higher voltage design.

The advantages of the ring-bar design compared to a helix tube are achieved at the expense of bandwidth. Ring-bar circuits are more "dispersive" than helix circuits and are, therefore, more limited in the range of operating frequency. The bandwidth of a ring-bar tube is generally in the order of 15% to 20%. With new bandwidth extension techniques, however, bandwidths of up to 50% and possibly more, are now feasible.

For some time, the TWT was considered usable only as a low-power device since the basic helix structure has the inherent tendency to oscillate at higher peak powers. In addition, the helix structure will not readily dissipate the large amount of heat that is accumulated at higher average powers. As a result, many other slow-wave structures were investigated in an effort to achieve wide bandwidth at high peak and average powers with good heat dissipation characteristics without the unwanted oscillations. Among the many types of circuits investigated, versions of the filter-type have demonstrated the greatest success.

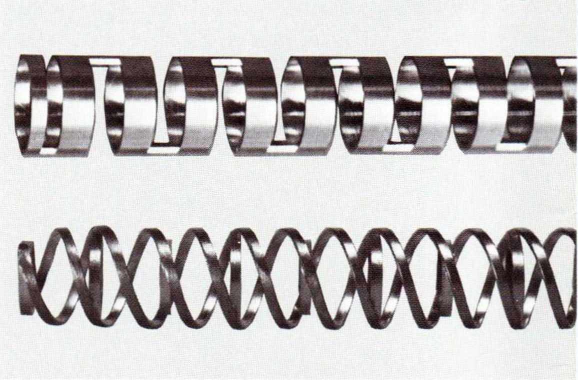
The simple waveguide is basically a high-pass filter. If a waveguide is periodically loaded, reflections will accumulate from the loading obstacles. The high pass filter then becomes a band-pass filter whose characteristics depend on the nature of the periodic loading. A number of circuits have been developed employing perturbation of the basic waveguide mode where the fundamental wave has its phase and group velocities in the same direction. One of these, the cloverleaf so named because the coupler resembles a fourleaf clover, has achieved up to 10 megawatts of peak power at S-band over a 10% frequency bandwidth with gains on the order of 20 to 40 dB.

Another broad group of circuits utilize a coaxial mode perturbed by the waveguide wall. The fundamental wave in these circuits has its phase and group velocities in opposite directions, so a harmonic, usually the first, is used. The single-slot, double-slot and drift tube are examples of spatial harmonic circuits. Double-slot TWTs have been built that produce one megawatt of peak-output power over a 9% bandwidth with gains also in the 20 to 30 dB region.

Development of the coupled-cavity circuit

One of the most significant developments in recent years has been the utilization of basic waveguide mode resonators that are coupled together by means of capacitive or inductive apertures to provide either a fundamental forward- or backward-wave circuit. The circuit, developed by Hughes, is known as the coupled-cavity circuit and is shown in Figure 7. It is also known as a folded-waveguide circuit since its structure resembles a waveguide folded up in accordian-like fashion.

Figure 6 Two variations on the basic helix structure are (a) the ring-bar structure, top and (b) the bifilar or folded helix, bottom.



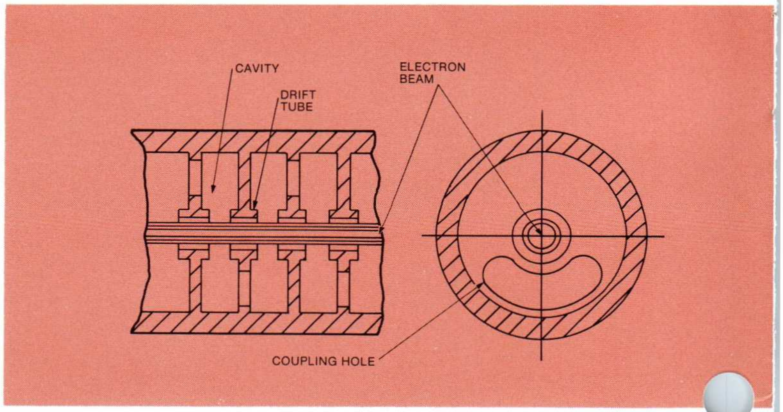


Figure 7 The coupled-cavity circuit, developed by Hughes is also known as a folded-waveguide circuit.

This structure provides the effective slowing of the RF energy to allow its synchronization with the electron beam just as the helix does in the structure defined in the preceding section. Figure 8 illustrates a cross-section view of a high power coupled-cavity tube of the spatial harmonic variety. The gun assembly is shown at the right end of the tube; input waveguide at the top right of the slow-wave structure; and the ouput to the left of the input. The cylindrical structure at the left is the collector. Focusing is provided by an integral solenoid.

Originally these structures provided frequency bandwidths on the order of 10 to 15%. Recently, however, means have been developed for increasing the bandwidth of these circuits to 40% and more. Tubes utilizing this circuit have been built and produce several hundred kilowatts of peak power at S- through Ku-bands with up to 60 dB gain. The inter-digital line is another version of the coupled-cavity circuit that has found extensive use in low and medium power amplifiers ranging up to one kW peak power output with gains of about 30 dB.

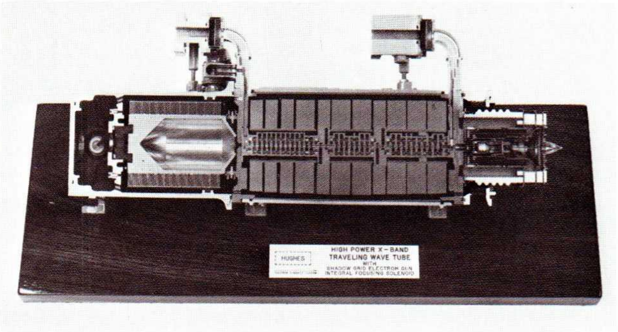
The focusing structure: constraining the electron beam

All TWTs require some means of holding the cylindrical electron beam in shape as it travels along the inner diameter of the interaction structure. This is due to the fact that the beam tends to disperse or spread out as a result of the mutual repulsive electrical forces between electrons. A magnetic field in varied forms is used for this purpose. Such a field of proper magnitude will confine the electron beam to the pencil-like cylindrical shape it must maintain. The four principle types of magnetic focusing discussed here are illustrated in Figure 9.

The solenoid is still regarded as one of the best magnetic focusing structures. It's magnetic lines are most parallel to the direction of travel of the electrons, and it can be accurately aligned with the beam. It provides excellent beam collimation and will continue to be used where the last bit of average power is required from a tube as long as tube size and weight are not critical factors. Most of the very high power TWTs to date have utilized solenoids.

In certain structures, however, where the interaction structure is short enough, permanent magnet focusing is often utilized in lieu of the bulky solenoid. Because of the length limitations, this type of focusing is generally restricted to low gain or low power tubes.

Figure 8 In this cross-section of a high-power coupled-cavity tube, the input waveguide is at the top right of the slow-wave structure and the output is at the left.



Perhaps the most profound development in beam control has been the evolution of double-period, periodic-permanent-magnet* (PPM) focusing — particularly its adaptation to high power TWTs. Previously, its fundamental limitations were thought to be so restrictive that it could only be utilized in low power TWTs where the beam power density is typically quite low.

One of the greatest needs for this lightweight focusing method is found at the high power levels where tubes, with focusing solenoids, have been too large and heavy for many airborne and space applications. PPM focusing has been successfully utilized to achieve 12 kW of average beam power in a 125 kW peak power pulse tube at S-band frequencies.

Figure 10 shows a cross-section view of the Hughes 774H, a high power pulsed helix TWT, complete with the focusing structure and external package. The tube is of metal-ceramic construction having a total weight of five pounds. The PPM focusing structure is composed of round magnet discs shown in the cross-section.

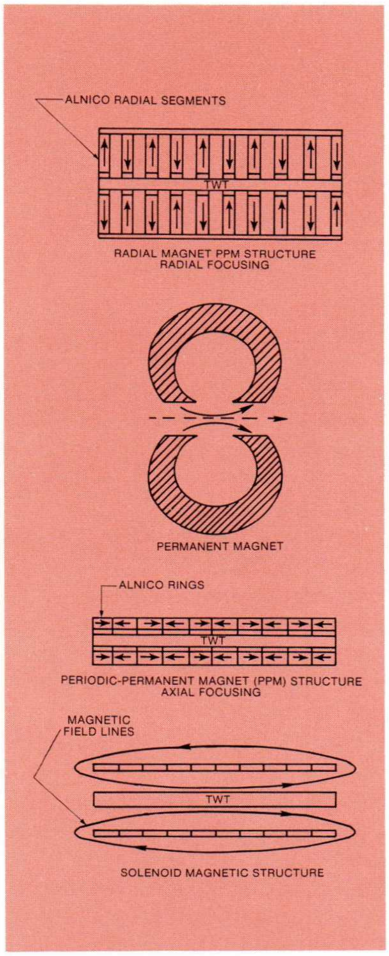
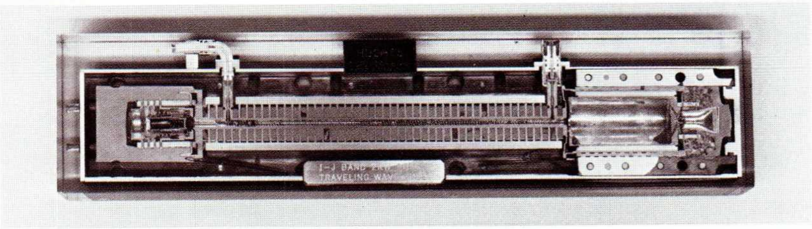


Figure 9 Among the four principal methods of magnetic focusing, the solenoid is considered the best choice.

Figure 10 The Hughes 774H X-band high-power helix TWT weighs only five pounds and is rated at 1.25 kW minimum power output with a 0.04 duty cycle.



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*Hughes U.S. patent no. 3,324,339

Dissipating the beam energy is the collector function

The collector dissipates the electrons in the form of heat as they emerge from the slow-wave structure. This is usually accomplished by thermal conduction to a colder outside surface where the heat is absorbed by circulated air or liquid. The specific collector is determined by the method of cooling used and the amount of energy that must be dissipated.

In order to improve the efficiency of some tubes, the collector may be operated at some voltage between ground and the cathode voltage. The voltage of the collector is brought closer to that of the cathode by introducing a power supply between the collector and cathode. Under these conditions, the tube is operating with a "depressed collector."

A typical collector may be "depressed" as much as 50%; that is, the collector voltage can be as much as one-half that of the cathode voltage. Since the electron beam is collected at some value less than the full cathode voltage, less energy is wasted. The result is a substantial increase in the overall efficiency of the tube.

Mechanical improvements upgrade TWT service

One of the major disadvantages of early helix circuit tubes was the fragile glass-vacuum envelope enclosing the tube parts. However, the art of packaging has reached the point where such glass structures are sufficiently well supported to withstand almost any environment and everything but the highest shock or G loads. Nevertheless, a recent innovation in the manufacturing of helix tubes has been the successful utilization of metal and ceramic materials in place of glass. These tubes can not only withstand higher G loads, but can be vacuum processed at higher temperatures—typically 600° to 700°C as opposed to 450°C in the case of glass structures. This ensures considerably more complete "bake-out" of undesirable gasses entrapped in the tube, thus providing improved reliability at higher tube operating temperatures.

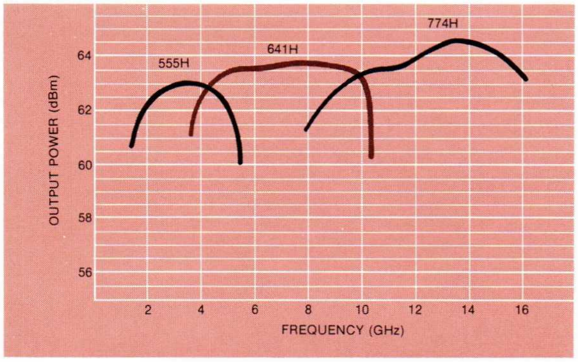
In a practical TWT, attenuators (lossy sections) are placed along the helix (slow-wave structure) to provide stability by absorbing internal and external mismatch relfections. The attenuators also isolate external system components on the output arm from those on the input arm. A typical high-gain TWT will provide up to 80 dB or more isolation or "cold" insertion loss. Without this "loss" added to the internal structure, it would be possible for reflected RF power to travel back to the input causing regeneration. In a high-gain device this would, in turn, cause a self-induced oscillation.

Since that portion of the slow-wave structure given over as attentuation does not contribute to the gain of the tube, the effect of adding attentuation increases the length of the device. The higher the gain, the more attenuator sections will be required. A rule-of-thumb is about 20 dB per section, so a tube with 50 dB gain would have three active sections and two attenuator sections.

When ECM systems demand high pulsed power and high CW power, broadband kW TWTs deliver

Hughes Electron Dynamics Division has been a leading supplier of broadband kilowatt level helix TWTs for many ECM systems. Proven production capability has been established with tubes in all the major frequency bands. Currently, pulsed kilowatt TWTs cover the ECM spectrum up to 18 GHz. Figure 1 shows RF output data for typical wideband pulsed helix tubes used in conventional ECM systems. Tube construction is rugged, metal-ceramic suitable for airborne or missile environments. These tubes use a single-gridded electron gun, PPM focusing and coaxial couplers.

Figure 1 The 2 to 18 GHz ECM band is covered with several pulsed helix TWT tubes using single-gridded electron guns, PPM focusing and coaxial couplers.



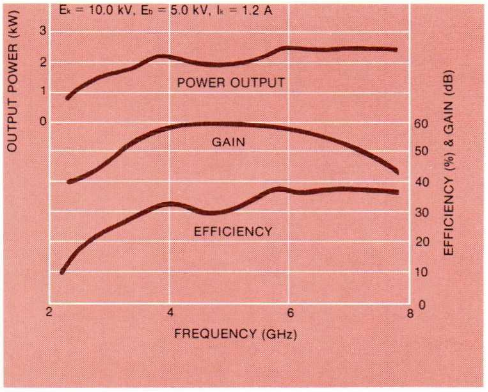
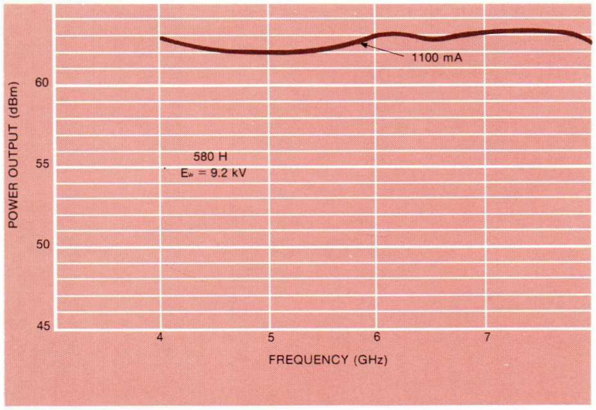


Figure 2 The new experimental Hughes 594H spans the 2.5 to 8.0 GHz band.

The Hughes 594H is a new developmental ECM pulsed tube with RF performance, as shown in Figure 2, covering the 2.5 to 8.0 GHz band. In the same band, the 580H also has good broadband performance from 4 to 8 GHz, as shown in Figure 3. In higher bands, the 8722H, an improved version of the 774H, has performance, as shown in Figure 4, of up to 18 GHz.

Figure 3 Excellent broadband performance from 4 to 8 GHz is offered by the Hughes 580H.



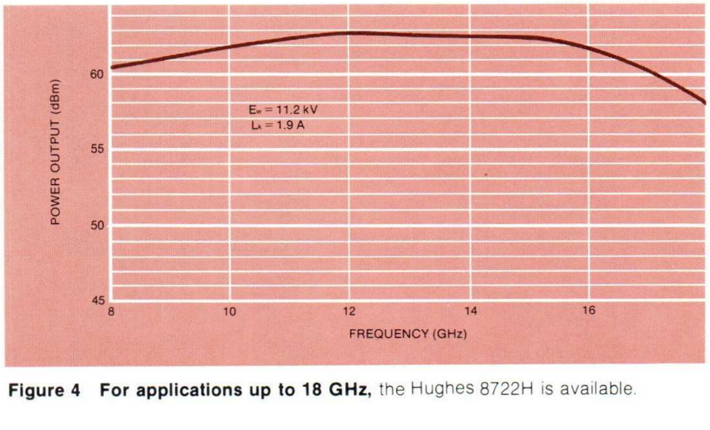


Figure 4 For applications up to 18 GHz, the Hughes 8722H is available.

The 869H variant of the 8722H shown in Figure 5, is also typical of the wideband performance now attainable for the design of ECM systems.

In addition to these pulsed types, the 551H, shown in Figure 6, is a high power CW TWT used in broadband airborne jammer applications. The integral solenoid provides a compact, rugged device for tactical environments. In recent years, these types of devices have been the conventional building blocks for ECM system designers, and in many instances, the equipment was capable of only one mode of operation—i.e., to provide either pulsed deceptive RF output or high power CW jamming. Currently, development work is underway at Hughes on 250 watt CW tubes in the 8 to 18 GHz bands for ECM and ground terminal applications.

Parallel pulsed TWTs

Figure 7 is a schematic of a technique to combine several kilowatt pused TWTs to attain higher pulsed power output. In such a combiner system, accurate phase tracking for all components over the frequency range is a critical requirement for satisfactory performance. The input dividers are 3 dB hybrids while the output combiners (hybrid or "magic T") have to be capable of handling higher peak and average power levels over large bandwidths. Phase compensation is required for each tube pair to ensure the correct phase relationship in each combiner. Each of the tubes also requires an amplitude and phase equalizer so phase tracking can be kept within +20° over an octave bandwidth provided that their grid and cathode voltages also are individually optimized. With these provisions, the combiner losses are still in the order of 1.5 dB over the band. Four tubes with 2.5 kW would, therefore, provide a combined peak power 7.0 kW.

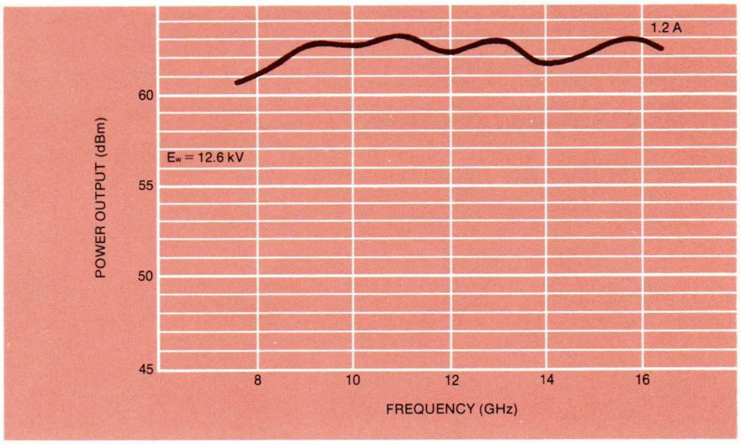


Figure 5 The Hughes 869H covers the 8 to 16 GHz band for ECM applications.

Figure 6 A typical application for this Hughes 551H high-power CW TWT is a broadband airborne jammer.

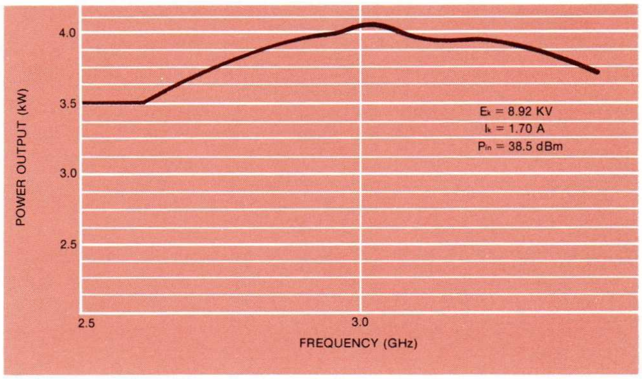
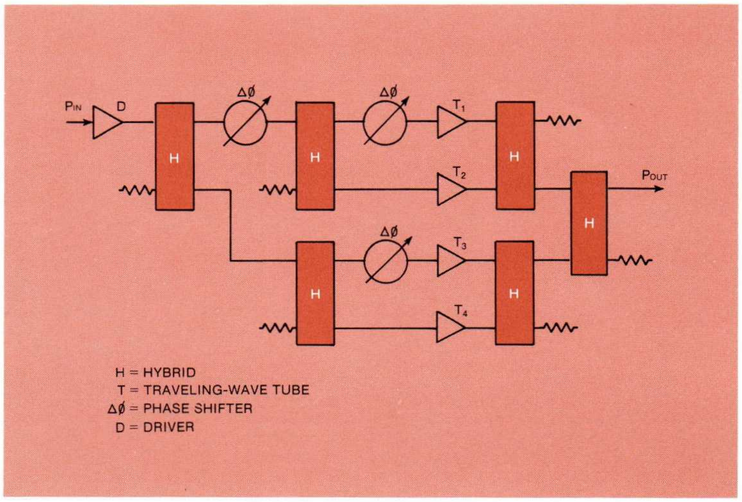


Figure 7 When combining several kilowatt pulsed TWTs to attain higher output, accurate phase tracking is critical.



New ECM TWTs

Modern electronic countermeasure systems, however, require simultaneous capability for high pulsed power and high CW power to adequately deter the threats in a modern tactical environment. At the same time, there are limited weight, space, cooling and prime dc power available in modern high performance aircraft. The ECM system designer, therefore, is continually under extreme pressure to enhance the overall efficiency of equipment and yet optimize the life-cycle costs.

For these reasons, the ECM system designer must usually evaluate several alternatives to best fulfill his system's performance requirements. One generic approach, shown in Figure 8, uses two TWTs operating in parallel from a single power supply. One is a pulsed TWT for deceptive schemes; the other a high power CW TWT used for jamming modes.

Newer system concepts utilize a single multi-mode TWT to provide either the pulsed or CW RF output. This approach has obvious simplicity as well as inherent savings in size and weight.

Key design features of this multi-mode device include a shadow gridded tetrode electron gun to provide the varied beam operating parameters. The helix circuit uses vane loading to achieve wider bandwidths as well as unique attenuators and velocity step tapering to inhibit backward-wave oscillations thereby enhancing tube stability. Integral barrel PPM focusing provides excellent RF performance as well as a reliable, rugged device.

Figure 9 shows multi-mode performance for the Hughes 869H TWT. This flexibility in providing for intermediate modes allows the designer to adapt the system to a wide range of output power requirements. Specific applications for such multi-mode performance should be discussed with Hughes at the time of system design to benefit from the latest developments in this area.

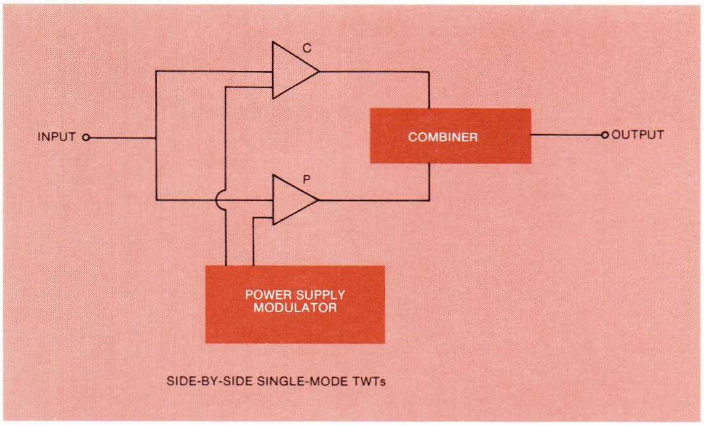
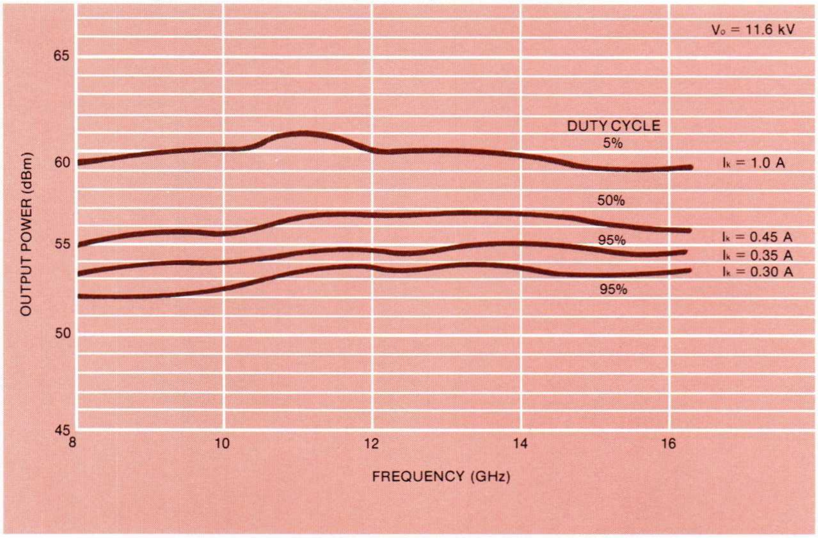


Figure 8 Two TWTs are operated in parallel from a single power supply, one pulsed TWT for deceptive schemes and the other as a high-power CW TWT for jamming.

Figure 9 Multi-mode performance of the Hughes' 869H offers the systems designer flexibility in output power requirements.



Radar and ECM TWTs

Pulsed TWTs

	Frequency Range (GHz)	Power Output (kW)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current 1k (A)
S-band	2.0-4.0	1.25	0.10	33	-7.8	1.8
	2.0-4.0*	1.0 p/0.2 CW	0.05	30	-7.8	1.8/0.300
	2.5-8.0	1.0	0.10	30	-10.0	2.5
	2.6-5.2	1.0	0.04	30	-9.0	2.0
	2.7-3.1	125.0	0.025	50	-45.0	17.0
	2.8-3.0	300.0	0.022	21	-57.0	28.0
	2.9-3.2	125.0	0.08	50	-45.0	17.0
	2.9-3.1	125.0	0.05	50	-45.0	17.0
	3.1-3.3	250.0	0.02	53	-53.0	21.0
	3.1-3.5	125.0	0.08	50	-42.0	17.0
C-band	4.0-8.0	1.0	0.02	30	-10.0	2.5
	4.0-8.0	1.25	0.1	30	-9.75	1.8
	4.0-8.0*	1.0 p/0.1 CW	0.05	40-23	-9.5	1.2/0.300
	5.3-5.7	65.0	0.04	50	-37.0	11.0
	5.4-5.7	50.0	0.025	50	-35.0	8.0
	5.4-5.8	75.0	0.033	46	-36.0	10.8
	5.4-5.8	75.0	0.025	50	-38.0	11.0
	5.4-5.8	165.0	0.035	47	-48.5	17.0
X-band	7.5-10.0	10.0	0.01	40	-32.0	7.0
	7.5-10.0	10.0	0.02	40	-33.0	7.0
	8.0-16.0*	1.0 p/0.1 CW	0.05	40/20	-11.0	1.2/0.300
	8.0-16.0	1.25	0.04	50	-11.0	2.1
	8.0-17.0	1.0	0.04	35	-11.5	2.1
	8.5-9.5	50.0	0.02	50	-36.0	10.3
	8.5-9.6	1.58	0.05	40	-11.0	1.5
	8.6-9.5	20.0	0.01	46	-24.0	6.0
	8.6-9.4	35.0	0.012	52	-30.0	7.8
	8.8-9.7	50.0	0.01	52	-32.0	7.6
	8.9-9.9	50.0	0.01	42	-30.0	8.0
	9.0-9.8	9.0	0.5	54	-18.0	2.5
	9.0-10.0	25.0	0.01	47	-24.0	5.5
	9.0-9.2	120.0	0.0025	50	-43.0	13.5
	9.2-9.9	40.0	0.05	54	-32.0	7.0
	9.2-9.5	26.0	0.012	52	-25.0	6.0
	9.2-10.0	50.0	0.04	56	-32.5	8.0
	9.25-9.75	25.0	0.02	45	-30.0	2.8
	9.3-9.9	50.0	0.02	50	-33.0	8.0
	9.3-9.9	50.0	0.10	47	-33.5	8.5
	9.3-10.0	26.0	0.012	52	-26.0	6.0
	9.37-9.57	40.0	0.005	45	-26.0	6.8
	9.55-9.85	2.5	0.5	53	-12.0	1.2
	9.6-9.8	1.0	0.20	50	-10.2	0.8
	9.6-10.2	50.0	0.05	52	-33.5	7.8
	9.7-9.9	15.0	0.02	58	-23.0	4.0
	10.0-10.3	4.0	0.20	33	-20.5	0.7
	11.0-17.0	5.0	0.02	40	-33.0	2.5
Ku-band	15.0-16.5	100.0	0.005	50	-62.0	7.8
	15.7-17.7	10.0	0.5	33	-30.0	3.4
	16.0-16.5	100.0	0.005	40	-62.0	8.0
	16.0-16.5	100.0	0.03	53	-65.0	8.1
	16.0-16.5	100.0	0.005	53	-63.0	7.7
	16.0-16.5	200.0	0.01	60	-85.0	13.0
	16.0-17.0	5.0	0.01	36	-24.0	1.5
	16.2-16.7	3.0	0.04	37	-22.0	1.3
	16.0-17.0	12.0	0.025	45	-30.0	2.0

▲ = under development
* = dual mode

CW TWTs

	Frequency Range (GHz)	Power Output (kW)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current 1k (A)
S	2.0-4.0	1.0	CW	30.0	-8.0	1.5
	2.0-4.0*	1.0 p - 0.2 CW	0.05	30.0	-7.8	1.8-0.300
C-band	4.0-8.0*	1.0 p - 0.1 CW	0.05	40.0-23.0	-9.5	1.2-0.300
	4.4-5.0	10.0	CW	11.0	-15.0	2.0
	7.5-10.5	1.0	CW	40.0	-9.8	1.2
X-band	8.0-16.0*	1.0 p - 0.1 CW	0.05	40.0-20.0	-11.0	1.2-0.300
	9.0-18.0	0.2	CW	30.0	-9.5	0.3
	10.0-10.2	0.5	CW	40.0	-16.0	0.25
Ku	13.6-14.0	5.0	CW	43.0	-18.5	1.5
	15.5-17.5	1.0	CW	30.0	-14.5	0.5
mm-wave	54.5-55.5	5.0	CW	20.0	-15.0	0.9
	59.7-60.3	0.05	CW	35.0	-15.5	0.060

* = dual mode
▲ = under development

Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number
17.5 x 2.5 dia	44.45 x 6.35 dia	10.0	3.73	PPM	SG	L	**555H**
17.5 x 2.5 dia	44.45 x 6.35 dia	10.0	3.73	PPM	SG	L	**562H**
19.0 x 3.63 x 2.56	48.26 x 9.22 x 6.5	8.0	2.99	PPM	SG	C	**658H**
15.0 x 2.25 x 2.25	38.1 x 5.72 x 5.72	9.0	3.36	PPM	SG	C	**554H**
58.0 x 6.0 dia	147.32 x 15.24 dia	205.0	76.51	PPM	SG	L	**589H**
41.0 x 6.0 dia	104.14 x 15.24 dia	185.0	69.04	PPM	SG	L	**584H**
57.0 x 6.0 dia	144.78 x 15.24 dia	20.0	7.46	PPM	SG	L	**588H**
56.0 x 6.0 dia	142.24 x 15.24 dia	195.0	72.77	PPM	SG	L	**587H**
54.0 x 6.0 dia	137.16 x 15.24 dia	180.0	67.18	PPM	SG	L	**▲560H**
52.0 x 6.0 dia	132.08 x 15.24 dia	170.0	63.44	PPM	SG	L	**559H**
14.5 x 2.75 dia	36.83 x 6.99 dia	10.0	3.73	PPM	SG	FA	**639H**
14.5 x 2.75 dia	36.83 x 6.99 dia	10.0	3.73	PPM	SG	L	**641H**
20.0 x 4.0 x 3.2	50.8 x 10.16 x 8.13	10.0	3.73	PPM	SG	C	**580H**
35.5 x 6.7 x 8.7	90.17 x 17.02 x 22.1	58.0	21.65	PPM	SG	L	**657H**
29.0 x 3.3 x 7.5	73.66 x 8.38 x 19.05	40.0	14.93	PPM	SG	L	**621H**
34.5 x 12.0 dia	87.63 x 30.48 dia	60.0	22.39	Sol	SG	L	**634H**
29.0 x 3.3 x 7.5	73.66 x 8.38 x 19.05	40.0	14.93	PPM	CP	L	**622H**
34.5 x 12.0	87.63 x 30.48	60.0	22.39	Sol	SG	L	**635H**
26.0 x 5.5 dia	66 04 x 13.97 dia	35.0	13.06	PPM	SG	L	**738H**
26.0 x 5.5 dia	66.04 x 13.97 dia	35.0	13.06	PPM	SG	L	**788H**
17.0 x 4.0 x 3.2	43.18 x 10.16 x 8.13	10.0	3.73	PPM	SG	C	**869H**
13.5 x 2.5 x 2.0	34.29 x 6.35 x 5.08	5.0	1.87	PPM	SG	C	**774H**
13.5 x 2.5 x 2.0	34.29 x 6.35 x 5.08	5.0	1.87	PPM	SG	C	**8722H**
21.0 x 5.0 dia	53.34 x 12.7 dia	30.0	11.20	PPM	A	L	**307H**
17.0 x 4.5 x 5.0	43.18 x 11.43 x 12.7	25.0	9.33	PPM	A	FA	**725H**
19.0 x 4.0 dia	48.26 x 10.16 dia	21.0	7.84	PPM	SG	FA	**308H**
20.0 x 4.5 dia	50.8 x 11.43 dia	26.0	9.7	PPM	SG	FA	**8718H**
20.5 x 5.5 dia	52.07 x 13.97 dia	25.0	9.33	PPM	SG	L	**751H**
16.5 x 5.5 dia	41.91 x 13.97 dia	22.0	8.21	PPM	CP	L	**760H**
21.0 x 6.0 x 8.0	53.34 x 15.24 x 20.32	45.0	16.79	IS	SG	L	**797H**
18.5 x 5.0 dia	46.99 x 12.7 dia	26.0	9.7	PPM	CP	FA	**750H**
24.0 x 5.0 dia	60.96 x 12.7 dia	35.0	13.06	PPM	CP	FA	**8716H**
20.5 x 5.5 dia	52.07 x 13.97 dia	28.0	10.45	PPM	SG	L	**796H**
20.5 x 5.0 dia	52.07 x 12.7 dia	26.0	9.7	PPM	SG	FA	**8709H**
24.0 x 5.5 dia	60.96 x 13.97 dia	32.0	11.94	PPM	SG	L	**8715H**
21.0 x 5.5 dia	53.34 x 13.97 dia	30.0	11.20	PPM	SG	L	**799H**
24.0 x 5.5 dia	60.96 x 13.97 dia	32.0	11.94	PPM	SG	L	**8740H**
21.0 x 6.5 dia	53.34 x 16.51 dia	45.0	16.79	IS	SG	L	**786H**
21.0 x 5.0 dia	53.34 x 12.7 dia	26.0	9.7	PPM	SG	FA	**8708H**
15.0 x 3.8 dia	38.1 x 9.65 dia	13.0	4.85	PPM	G	FA	**719H**
16.0 x 6.0 x 7.5	40.64 x 15.24 x 19.05	37.0	13.81	IS	SG	L	**781H**
16.0 x 4.0 dia	40.64 x 10.16 dia	13.0	4.85	PPM	SG	FA	**790H**
24.0 x 5.5 dia	60.96 x 13.97 dia	32.0	11.94	PPM	SG	L	**8701H**
18.0 x 3.3 dia	45.72 x 8.38 dia	10.0	3.73	PPM	SG	FA	**8725H**
17.0 x 4.5 dia	43.18 x 11.43 dia	17.0	6.34	PPM	SG	L	**8741H**
20.0 x 4.0 dia	50.8 x 10.16 dia	18.0	6.72	PPM	SG	L	**867H**
18.0 x 4.25 dia	45.72 x 10.8 dia	19.0	7.09	PPM	CP	L	**839H**
30.0 x 7.0 dia	76.2 x 17.78 dia	65.0	24.26	IS	A	L	**866H**
19.0 x 5.0 x 6.0	48.26 x 12.7 x 15.24	20.0	7.46	PPM	CP	L	**605H**
20.0 x 6.0 dia	50.8 x 15.24 dia	45.0	16.79	IS	SG	L	**854H**
16.0 x 4.0 dia	40.64 x 10.0 dia	15.0	5.6	PPM	SG	L	**838H**
27.0 x 6.0 dia	68.58 x 15.24 dia	30.0	11.2	PPM	SG	L	**835H**
14.0 x 3.5 dia	35.56 x 8.89 dia	15.0	5.6	PPM	SG	L	**820H**
16.0 x 4.5 dia	40.64 x 11.43 dia	14.0	5.22	PPM	SG	L	**830H**
14.0 x 4.0 dia	35.56 x 10.0 dia	12.0	4.48	PPM	SG	L	**861H**

Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number
2.0 x 3.0 dia	5.08 x 7.62 dia	22.0	8.21	Sol	A	L	**551H**
17.5 x 2.5 dia	44.45 x 6.35 dia	10.0	3.73	PPM	SG	L	**562H**
20.0 x 4.0 x 3.2	50.8 x 10.16 x 8.13	10.0	3.73	PPM	SG	C	**580H**
36.0 x 12.0 dia	91.44 x 30.48 dia	175.0	65.31	IS	A	V	**636H**
24.0 x 6.0 dia	60.96 x 15.24 dia	57.0	21.24	IS	A	L	**8713H**
17.0 x 4.0 x 3.2	43.18 x 10.16 x 8.13	10.0	3.73	PPM	SG	C	**869H**
17.0 x 3.0 x 2.8	43.18 x 7.62 x 7.11	8.0	2.99	PPM	A	C	**8730H**
14.2 x 2.0 dia	36.07 x 5.08 dia	7.5	2.8	PPM	CP	L	**8731H**
2.0 x 6.0 dia	55.88 x 15.24 dia	60.0	22.39	IS	A	L	**875H**
20.0 x 7.0 dia	50.80 x 17.78 dia	65.0	24.26	Sol	A	L	**832H**
25.0 x 12.0 x 12.0	63.50 x 30.48 x 30.48	60.0	22.39	Sol	CP	L	**▲819H**
14.0 x 4.0 x 5.0	35.56 x 10.16 x 12.70	13.0	4.85	PPM	CP	C	**920H**

Communications TWTs and TWTAs

Space type CW TWTs[1]

	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Cathode Voltage Ek (kV)
L	1.5-1.6	7.0, 26.0, 60.0	23, 33, 47	-2.63
	1.5-2.0	12.0	28	-1.2
S-band	2.0-2.1	26.0	44	-2.4
	2.2-2.4	8.0	27	-0.93
	2.5-2.7	100.0	42	-3.3
	2.5-2.7	50.0	4	-2.54
	3.0-3.5	10.0	43	-1.8
	3.7-4.2	5.5	55	-1.3
	3.7-4.2	4.5	54	-1.3
	3.7-4.2	8.5	57	-1.6
	3.7-4.2	6.0	57	-1.2
	3.7-4.2	1.5	35	-1.63
	3.7-4.2	5.0	55	-1.3
	3.7-4.2	0.5	31	-1.05
	3.7-4.2	5.5	55	-1.35
	3.7-4.2	5.0	55	-1.28
C-band	5.9-6.4	100.0	33	-3.6
	6.0-9.0	20.0	40	-3.4
	6.0-9.0	16.0	46	-3.4
	7.0-8.0	0.5	32	-1.75
	7.0-8.0	40.0	53	-4.0
	7.0-8.0	10.0	50	-2.6
	7.0-9.0	22.0	46	-3.8
	7.9-8.4	50.0	33	-4.25
X-band	8.0-9.0	20.0	40	-3.4
	8.4-8.5	24.0	37	-3.3
	10.0-15.0	1.2	45	-1.86
	10.5-13.0	10.0	54	-3.0
	11.0-12.0	12.0	47	-2.93
	11.0-12.0	20.0	57	-4.06
	11.9-12.1	1.3	45	-1.88
	11.9-13.8	1.5	44	-2.0
	11.95-12.13	100.0	40	-8.1
	12.0-16.0	1.0	45	-1.84
	12.038-12.123	250.0	38	-8.2
Ku-band	13.0-14.0	20.0	48	-3.45
	13.0-14.0	1.0	45	-1.85
	13.5-14.0	20.0	53	-3.55
	13.7-14.1	1.0	45	-1.88
	13.8-15.0	60.0	47	-5.0
	14.0-15.0	16.0	46	-3.45
	14.0-15.0	16.0	46	-3.45
	14.52-14.68	100.0	40	-8.0
	14.85-15.15	15.0	45	-3.4
	17.75-20.25	4.0	50	-4.5
K	18.0-22.0	2.0	42	-3.9
	19.0-23.0	30.0	55	-6.75
mm-wave	29.0-31.0	2.0	42	-5.5
	30.0-32.0	3.0	43	-5.4
	41.0-43.0	200.0	47	-21.0
	42.0-42.5	100.0	44	-14.5
	84.0-86.0	200.0	47.0	-25.0

* = dual mode
▲ = under development

[1] All models are PPM focussed and conduction cooled unless otherwise noted.
[2] Anode mod control [3] Aperature grid [4] Conduction/radiation cooling [5] Radiation cooling

Cathode Current Ik (A)	Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Model Number
0.014, 0.027, 0.057	20.2 x 4.3 x 2.7	51.31 x 10.92 x 6.86	9.0	3.36	**291H**
0.05	11.5 x 1.6 x 1.6	29.21 x 4.06 x 4.06	1.4	0.52	**414H**
0.046	17.5 x 2.25 x 2.5	44.45 x 5.72 x 6.35	5.0	1.87	**278H**
0.04	8.25 x 3.0 x 1.1	20.96 x 7.62 x 2.79	1.0	0.37	**214H**
0.1	14.5 x 2.6 x 3.0	36.83 x 6.60 x 7.62	4.2	1.57	**283H**
0.056	15.0 x 2.0 x 2.0	38.10 x 5.08 x 5.08	3.5	1.31	**297H**
0.04	11.0 x 1.6 x 1.4	27.94 x 4.06 x 3.56	1.2	0.45	**235H**
0.022	12.4 x 1.9 x 2.3	31.50 x 4.83 x 5.84	1.25	0.47	**230H**
0.022	12.4 x 1.9 x 2.3	31.5 x 4.83 x 5.84	1.6	0.60	**244H**
0.03	13.0 x 1.9 x 2.3	33.02 x 4.83 x 5.84	1.7	0.63	**249H**
0.025	12.3 x 1.9 x 1.8	31.24 x 4.83 x 4.57	1.75	0.65	**271H**
0.09	12.0 x 1.9 x 1.84	30.48 x 4.83 x 4.67	1.31	0.49	**272H**
0.022	12.0 x 1.9 x 1.75	30.48 x 4.83 x 4.45	1.5	0.56	**275H**
0.005	10.2 x 1.9 x 1.84	25.91 x 4.83 x 4.67	1.2	0.45	**276H**
0.025	12.0 x 2.3 x 1.8	30.48 x 5.84 x 4.57	1.5	0.56	**277H**
0.021	12.1 x 1.9 x 2.3	30.73 x 4.83 x 5.84	1.4	0.52	**296H**
0.085	12.0 x 2.5 x 2.5	30.48 x 6.35 x 6.35	3.0	1.12	**279H**
0.042	12.3 x 3.0 x 1.5	31.24 x 7.62 x 3.81	2.75	1.03	**240H**
0.040	12.5 x 4.6 x 2.2	31.75 x 11.68 x 5.59	3.1	1.16	**240HA**
0.005	9.6 x 1.1 x 1.4	24.38 x 2.79 x 3.56	1.0	0.37	**263H**
0.053	13.25 x 2.5 x 2.5	33.66 x 6.35 x 6.35	3.6	1.34	**293H**
0.026	11.4 x 2.18 x 1.7	28.96 x 5.5 x 4.32	1.5	0.56	**298H**
0.05	12.0 x 2.2 x 1.3	30.48 x 5.59 x 3.30	2.2	0.82	**265H**
0.057	11.7 x 1.6 x 2.0	29.72 x 4.06 x 5.08	2.25	0.84	**287H**
0.04	10.5 x 2.3 x 1.7	26.67 x 5.84 x 4.32	1.5	0.56	**219H**
0.036	11.7 x 1.6 x 2.0	29.72 x 4.06 x 5.08	2.25	0.84	**285H**
0.009	9.4 x 1.7 x 1.8	23.88 x 4.32 x 4.57	1.2	0.45	**837H**
0.029	9.8 x 1.9 x 1.6	24.89 x 4.83 x 4.06	1.25	0.47	**280H**
0.03	10.0 x 2.0 x 2.0	25.4 x 5.08 x 5.08	1.8	0.67	**▲286H**
0.038	13.0 x 2.0 x 2.0	33.02 x 5.08 x 5.08	2.0	0.75	**▲286HP**
0.01	9.4 x 1.7 x 1.8	23.88 x 4.32 x 4.57	1.2	0.45	**837HD**
0.01	11.0 x 1.9 x 2.6	27.94 x 4.83 x 6.60	1.8	0.67	**845H**
0.056	21.0 x 6.0 dia	53.34 x 15.24 dia	14.6	5.45	**294H**[2,4]
0.009	10.0 x 1.9 x 2.7	25.40 x 4.83 x 6.86	1.4	0.52	**837HA**
0.092	18.0 x 9.8 dia	45.72 x 24.89 dia	26.2	9.78	**284H**[2,4]
0.042	10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.4	0.90	**295H**
0.009	9.4 x 1.7 x 1.8	23.88 x 4.32 x 6.86	1.2	0.61	**837HB**
0.05	10.0 x 1.9 x 2.7	25.40 x 4.83 x 6.86	1.63	0.61	**851H**
0.01	10.3 x 1.9 x 2.3	26.16 x 4.83 x 5.84	1.4	0.52	**837HC**
0.075	14.0 x 4.0 x 3.0	35.56 x 10.16 x 7.62	6.0	2.24	**▲874H**
0.041	10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.5	0.93	**264H**
0.042	10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.4	0.90	**288H**
0.056	21.0 x 6.0 dia	53.34 x 15.24 dia	14.6	5.45	**8294H**[3,4]
0.04	10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.4	0.90	**288HC**
0.017	12.0 x 1.5 x 1.5	30.48 x 3.81 x 2.81	1.9	0.71	**292H**
0.013	9.6 x 1.8 x 2.0	24.38 x 4.57 x 5.08	1.2	0.45	**268H**
0.05	13.5 x 3.0 x 3.0	34.29 x 7.62 x 7.62	2.0	0.75	**▲250H**[2]
0.007	10.0 x 1.9 x 1.9	24.50 x 4.83 x 4.83	1.2	0.45	**254H**
0.012	12.4 x 2.5 x 2.0	31.50 x 6.35 x 5.08	1.8	0.67	**251H**
0.095	14.0 x 5.0 x 5.0	35.56 x 12.7 x 12.70	15.0	5.60	**▲943H**[5]
0.046	17.0 x 5.0 x 5.0	43.18 x 12.70 x 12.70	15.0	5.60	**▲944H**
0.160	18.0 x 6.0 x 6.0	45.72 x 15.24 x 15.24	18.0	6.72	**▲985H**[5]

Communications TWTs and TWTAs (cont.)

Space type CW TWTAs

	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Input Voltage (Vdc)
S-band	2.0-2.1	26.0	44	22-42
	2.2-2.3	15.0	30	22-32
	3.7-4.2	4.5	54	22-42
	3.7-4.2	8.5	57	22-42
	3.7-4.2	5.5	45	22-42
	3.7-4.2	5.0	53	24-36
C-band	4.1-4.2	0.2	51	28± 2%
	6.0-10.0	20.0	48	22-33
	7.0-8.0	0.5	32	23-33
	7.0-8.0	40.0	53	22-33
	7.0-8.0	40.0	53	22-33
	7.0-9.0	22.0	46	23-33
	7.25-7.75	10.0	50	22-33
	7.25-7.75	40.0	53	22-33
X	11.9-12.1	1.0	45	26-29
	11.9-13.8	1.5	55	22-42
Ku-band	13.0-14.0	20.0	48	23-35
	13.25-13.75	2000†	43	24-33
	13.5-14.5	1.5	40	24-30
	13.5-14.5	20.0	53	24-30
	14.0-15.0	16.0	46	23-35
	14.0-15.0	16.0	46	23-35
	14.85-15.15	15.0	45	21-35
	17.75-20.25	4.0	50	24-32
mm	30.0-32.0	3.0	43	2.8-29.6

*Electronic power conditioner

†Pulsed 0.33% duty

Ground terminal TWTs

	Frequency Range (GHz)	Power Output (kW)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current Ik (A)
C-band	5.2-5.8	3.0	CW	46.0	−13.5	1.8
	5.925-6.425	0.8	CW	40.0	−13.5	0.62
	5.925-6.425	8.0	CW	40.0	−18.0	2.8
	7.9-8.4	1.2	CW	30.0	−9.9	0.09
	7.9-8.4	40.0	0.014	50.0	−32.0	7.5
	7.9-8.4	3.0	CW	35.0	−13.4	1.48
	7.9-8.4	5.0	CW	35.0	−13.4	2.05
	7.9-8.4	14.0	CW	38.0	−22.0	2.7
	7.9-8.4	8.0	CW	36.0	−18.0	2.2
	7.9-8.4	0.6 - 1.2	CW	40.0	−13.2	0.72
Ku	14.0-14.5	5.0	CW	35.0	−19.0	1.7
	14.0-14.5	0.2	CW	30.0	−9.0	0.260
	14.0-14.5	0.6	CW	43.0	−15.0	0.33
mm-wave	30.0-31.0	0.2	CW	35.0	−18.0	0.08
	36.4-38.4	0.1	CW	45.0	−16.0	0.078
	49.5-58.0	0.15	CW	12.0	−20.0	0.12
	54.5-55.5	1.0	CW	25.0	−25.0	0.4
	91.0-96.0	0.10	CW	25.0	−15.0	0.17

▲Under development

Ground terminal TWTAs

	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Input Voltage (Vac,Ø)
C-band	5.9-6.4	40.0	45	120,1
	5.9-6.4	350.0	55	120,1
	7.9-8.4	40.0	43	120,1
Ku	14.0-14.5	20.0	53	120,1
	14.0-14.5	600.0	45	120/208, 3

▲Under development

Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	TWT Model Number	Amplifier Model Number
13.7 x 3.0 x 4.0	34.93 x 7.62 x 10.16	7.5	2.80	278H	**1266H**
11.0 x 6.0 x 4.2	27.94 x 15.24 x 10.67	8.5	3.17	256H	**1190H**
13.5 x 4.0 x 3.25	33.66 x 10.16 x 8.26	4.6	1.72	244H	**1243H**
13.25 x 4.0 x 3.25	33.66 x 10.16 x 8.26	5.0	1.87	249H	**1244H**
13.25 x 4.0 x 3.25	33.66 x 10.16 x 8.26	3.2	1.19	230H	**1264H**
13.3 x 3.5 x 3.3	33.78 x 8.89 x 8.38	3.75	1.40	296H	**1288H**
11.0 x 3.5 x 1.7	27.94 x 8.9 x 4.32	2.7	1.01	233HC	**1224H**
12.0 x 6.1 x 4.1	30.48 x 15.5 x 10.41	9.6	3.58	265HA	**1240H**
10.0 x 4.0 x 2.5	25.4 x 10.16 x 6.35	4.5	1.68	263H	**1200H**
15.15 x 6.0 x 4.7	38.48 x 15.24 x 11.94	15.75	5.88	293H	**1238H**
15.15 x 6.0 x 4.7	38.48 x 15.24 x 11.94	16.5	6.16	293HA	**1241H**
12.0 x 5.0 x 3.0	30.48 x 12.7 x 7.62	9.5	3.55	265H	**1202H**
13.6 x 4.3 x 4.3	34.54 x 10.92 x 10.92	6.5	2.43	298H	**1248H**
15.15 x 6.0 x 4.7	38.48 x 15.24 x 11.94	15.0	5.59	293HB	**1255H**
11.4 x 5.1 x 2.6	28.96 x 12.95 x 6.6	4.4	1.64	837HD	**1292H**
13.25 x 4.0 x 3.25	33.66 x 10.16 x 8.26	3.5	1.31	845H	**1268H**
13.0 x 4.4 x 3.7 *	33.02 x 11.18 x 9.4	7.0*	2.61*	295H	**1250H**
16.25 x 6.75 x 6.25 *	41.28 x 17.15 x 15.88	30.0	11.20	853H	**1256H**
11.0 x 5.7 x 2.5	27.94 x 14.48 x 6.35	6.0	2.24	837HA	**1218H**
12.0 x 6.5 x 4.25	30.48 x 16.51 x 10.8	9.25	3.45	851H	**1220H**
13.0 x 4.4 x 3.7 *	33.02 x 11.18 x 9.4	7.0*	2.61*	288H	**1230H**
13.0 x 4.4 x 3.7 *	33.02 x 11.18 x 9.4	7.0*	2.61*	264H	**1260H**
10.5 x 4.0 x 4.5 *	26.76 x 10.16 x 11.43	7.7	2.87	288HC	**1245H**
13.25 x 4.2 x 3.5	33.66 x 10.67 x 8.89	4.8	1.79	292H	**1294H**
13.25 x 4.4 x 3.4	33.66 x 11.18 x 8.64	5.5	2.05	251H	**1254H**

Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number
27.0 x 8.0 x 8.0	68.58 x 20.32 x 20.32	140.0	52.25	IS	A	L	**663H**
32.0 x 6.5 dia	81.28 x 16.51 dia	65.0	24.26	PPM	A	FA	**644H**
34.0 x 7.5 dia	86.36 x 19.05 dia	95.0	35.45	Sol	A	L	**614H**
18.0 x 6.0 dia	45.72 x 15.24 dia	42.0	15.67	Sol	A	L	**745H**
22.0 x 5.5 dia	55.88 x 13.97 dia	30.0	11.2	PPM	SG	L	**751H/103**
21.0 x 6.1 dia	53.34 x 15.49 dia	68.0	25.38	IS	A	L	**767H**
21.0 x 6.1 dia	53.34 x 15.49 dia	65.0	0.24	IS	A	L	**792H**
27.0 x 6.8 dia	68.58 x 17.27 dia	120.0	44.78	IS	A	L	**8723H**
24.0 x 6.1 dia	60.96 x 15.49 dia	80.0	29.86	IS	A	L	**784H**
26.0 x 6.3 dia	66.04 x 16.0 dia	40.0	14.93	PPM	A	FA	**8760H**
30.0 x 7.0 dia	26.20 x 17.78 dia	65.0	0.24	IS	A	L	**870H**
17.0 x 3.0 x 3.0	43.18 x 7.62 x 7.62	10.0	3.73	PPM	A	FA	**▲8730H**
23.0 x 6.0 dia	58.42 x 15.24 dia	30.0	11.20	PPM	A	FA	**▲876H**
14.0 x 4.0 dia	35.56 x 10.16 dia	12.0	4.48	PPM	A	FA	**914H**
14.0 x 4.0 dia	35.56 x 10.16 dia	12.0	4.48	PPM	A	FA	**913H**
15.0 x 4.0 x 10.0	38.1 x 10.16 x 25.4	17.0	6.34	PPM	CP	L	**▲812H**
18.0 x 10.0 x 12.0	45.72 x 25.4 x 30.48	50.0	18.66	Sol	CP	L	**▲813H**
18.0 x 9.0 x 10.0	45.72 x 22.66 x 25.40	40.0	14.93	Sol	CP	L	**▲814H**

Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	TWT Model Number	Amplifier Model Number
15.6 x 19.0 x 3.5	39.62 x 48.26 x 8.89	20.0	7.46	670HA	**9040H02**
19.0 x 23.0 x 21.0	48.26 x 58.42 x 53.34	170.0	63.44	662H	**9240H02**
15.6 x 19.0 x 3.5	39.62 x 48.26 x 8.89	20.0	7.46	8736H	**9040H03**
15.6 x 19.0 x 3.5	39.62 x 48.26 x 8.89	20	7.46	848HA	**9020H04**
19.0 x 24.0 x 67.0	48.26 x 60.96 x 170.18	240.0	89.57	876H	**▲9360H04**

TWT amplifiers

	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Input Voltage (Vac,Ø)
S	2.0-4.0	8.0	35	115,3
	2.9-3.1	3000[1]	70	115,3
C	4.0-8.0	20.0	38	115,3
X	8.0-12.4	4.0	33	115,3
Ku	12.4-18.0	5.0	37	115,3
mm	37.0-38.0	2.0	30	28-34 dc

[1] Pulsed 0.0025% duty

Instrumentation power amplifiers

	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Dimensions L x W x H (inches)
L-band	1.0-2.0	10	30	15.5 x 16.75 x 3.5
	1.0-2.0	20	30	15.5 x 16.75 x 3.5
	1.4-2.4	20	30	15.5 x 16.75 x 3.5
S-band	2.0-4.0	10	30	15.5 x 16.75 x 3.5
	2.0-4.0	20	30	15.5 x 16.75 x 3.5
	2.5-4.0	20	30	15.5 x 16.75 x 3.5
	3.0-8.0	10	30	15.5 x 16.75 x 3.5
	3.9-11.7	10*	30*	15.5 x 16.75 x 3.5
C-band	4.0-8.0	10	30	15.5 x 16.75 x 3.5
	4.0-8.0	20	30	15.5 x 16.75 x 3.5
	4.0-10.5	10	30*	15.5 x 16.75 x 3.5
	5.0-10.0	10	30	15.5 x 16.75 x 3.5
	6.5-13.5	10	30	15.5 x 16.75 x 3.5
	7.0-16.5	10	30	15.5 x 16.75 x 3.5
X-band	8.0-12.4	10	30	15.5 x 16.75 x 3.5
	8.0-12.4	20	30	15.5 x 16.75 x 3.5
	8.0-18.0	10	30	15.5 x 16.75 x 3.5
	10.5-18.0	10	30	15.5 x 16.75 x 3.5
Ku	12.4-18.0	10	30	15.5 x 16.75 x 3.5
	12.4-18.0	20	30	15.5 x 16.75 x 3.5
K	18.0-26.0	1	30	15.5 x 16.75 x 3.5

Note: Each amplifier contains a PPM-focused, metal-ceramic TWT; all solid-state, air-cooled power supply in a 19-inch instrument case.
Options: Isolator/circulators, high gain, and automatic reset. 220/240 ac or 28/48 dc input voltage, unattended protection, rack mounting, local/remote, 48 to 420 Hz, logic circuit (TTL).
Warranty: One year regardless of operating hours.
*Slightly lower at band edges.

Klystrons

	Frequency Range (GHz)	Minimum Power Output (W)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current 1k (A)
X-band	9.2-9.4	100	0.33	30.0	−3.0	0.15
	9.2-9.4	100	0.33	40.0	−3.0	0.15
	9.2-9.4	100	0.33	40.0	−3.0	0.15
	9.2-9.4	100	0.5	30.0	−3.3	0.20
	10.0-10.25	200	CW	40.0	−3.6	0.22
Ku	12.6-12.9	36	CW	40.0	−2.0	0.10

Symbols

A = mod anode
C = conduction
CP = cathode pulse
FA = forced air
G = high mu grid
IS = integral solenoid
L = liquid
PM = permanent magnet
PPM = periodic-permanent magnet
SG = shadow grid
Sol = solenoid
V = vapor phase

Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	TWT Model Number	Amplifier Model Number
19.0 x 6.5 x 7.0	48.26 x 16.51 x 17.78	18.5	6.90	564H-8	**1233H**
20.0 x 4.0 x 8.0	50.8 x 10.16 x 20.32	28.0	10.45	543H - 544H	**1160H**
19.0 x 6.5 x 7.0	48.26 x 16.51 x 17.78	18.5	6.90	640H-8	**1234H**
19.0 x 6.5 x 7.0	48.26 x 16.51 x 17.78	18.5	6.90	771H-8	**1235H**
19.0 x 6.5 x 7.0	48.26 x 16.51 x 17.78	18.5	6.90	848H-8	**1236H**
13.5 x 8.0 x 3.5	34 29 x 20.32 x 8.89	8.0	2.99	863H	**1228H**

Dimensions L x W x H (cms)	Weight (pounds)	Weight (kgs)	Connector Type	Input Voltage (Vac, 1 Ø)	Input Frequency (A)	TWT Model Number	Amplifier Model Number
39.37 x 42.55 x 8.89	25	11.35	N	115	50/60	417H	**1177H09F000**
39.37 x 42.55 x 8.89	25	11.35	N	115	50/60	418H	**1277H09F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	419H	**1177H10F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	564H	**1177H01F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	568H	**1277H01F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	564HS	**1177H05F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	646H	**1177H13F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	664H	**1177H16F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	648H	**1177H02F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	640H	**1277H02F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	648HS	**1177H06F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	746H	**1177H14F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	771HS	**1177H07F000**
39.37 x 42.55 x 8.89	20	9.08	SMA	115	50/60	785H	**1177H17F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	771H	**1177H03F000**
39.37 x 42.55 x 8.89	20	9.08	N	115	50/60	783H	**1277H03F000**
39.37 x 42.55 x 8.89	20	9.08	SMA	115	50/60	846H	**1177H15F000**
39.37 x 42.55 x 8.89	20	9.08	UG-419/U	115	50/60	848HS	**1177H08F000**
39.37 x 42.55 x 8.89	20	9.08	UG-419/U	115	50/60	848H	**1177H04F000**
39.37 x 42.55 x 8.89	20	9.08	UG-419/U	115	50/60	856H	**1277H04F000**
39.37 x 42.55 x 8.89	20	9.08	WR-42	115	50/60	911H	**1077H11F000**

Dimensions L x W x H (inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number
5.0 x 3.5 x 3.5	12.7 x 8.89 x 8.89	4.5	1.68	PM	CP	L	**173H**
5.0 x 3.5 x 3.5	12.7 x 8.89 x 8.89	4.5	1.68	PM	CP	FA	**793H**
5.0 x 3.5 x 3.5	12.7 x 8.89 x 8.89	4.5	1.68	PM	G	FA	**8710H**
5.0 x 3.5 x 3.5	12.7 x 8.89 x 8.89	4.5	1.68	PM	G	C	**8734H**
6.0 x 4.0 x 4.0	15.24 x 10.16 x 10.16	5.0	1.87	PM	CP	FA	**173H Mod.**
6.0 x 3.9 x 5.5	15.24 x 9.1 x 13.97	7.25	2.71	PM	CP	FA	**8702H**

Space TWTAs: It's life that counts

Just how long can a TWT amplifier (TWTA) be expected to perform in a space application? Life experience approaching 15,000,000 hours indicates that 10 years is a reasonable estimate for the life of Hughes space hardware.

The key amplifying element of most spacecraft is the TWTA. A photo of a typical driver and output TWTA is shown in Figure 1. These microwave amplifiers provide the necessary high-power gain required for transmission as well as overcoming system losses. This high gain is accomplished at a moderate cost in primary power due to the overall high conversion efficiency of the TWT and the electronic power conditioner (EPC).

Hughes space experience began in 1963 with the launch of the Syncom Satellite series. These Hughes/NASA satellites were the first attempt at placing satellites in synchronous orbit. Syncom also contained the first of a continuing line of space TWTs. Since our beginning in 1963, Hughes has in-orbit operating time approaching 10,000,000 hours. This is in addition to the life test experience of nearly 5,000,000 hours. The in-orbit experience has been accumulated on over 35 major space programs — Apollo, Mariner, Surveyor, Pioneer, Intelsat series, Skylab, Westar, Marisat, and DSCS-II, to name a few.

While Hughes experience began in the early 60s for TWT development, its experience in specifying, integrating, and testing TWTAs began in the mid-60s with the Lunar Orbiter program. Since that time, TWTAs have been developed and delivered for military, NASA, commercial and international space applications. The RF-power capabilities of such units range from 200 mW to 100 W of CW operation. Hughes has ongoing programs to investigate higher efficiency, lower weight, smaller size, higher reliability, the interface problems between TWT and the EPC, and the interface between the TWTA and the spacecraft.

The space TWT: Quite a device

The design philosophy adopted for the TWT during the Syncom era provided hardware that was rugged, reliable, lightweight, and with a long service life. The same philosophy has carried over in the more recent programs to achieve the same desirable features for the EPC. While maintaining the original design philosophy, Hughes has developed and implemented the most up-to-date state-of-the-art technology in the areas of metal-ceramics processing and mechanical and electrical design techniques. This combination of philosophy and technology has produced hardware that has consistently proved itself to be space-qualified.

The electron beam: Key to a long-life TWT

The key element in a long-life, space-qualified TWT is the electron beam. In order to attain high reliability and long life, extreme care is taken in the design of the beam source—the cathode. In a properly designed tube, cathode life is the main factor in determining tube life. All other wear-out or failure mechanisms have been minimized by efficient, conservative design and processing. To achieve this long life without RF power degradation, an oxide cathode was selected for the Syncom TWT. This type of cathode has been used in all of our long-life space TWTs and has become the key factor, based upon life data and actual space operation, for Hughes to insure a stable 10 year life.

Electron gun optics are selected for conservative space charge, limited emission density and cathode temperature at a perveance, voltage, and beam size appropriate to the tube design.

Other factors that must be taken into account to insure long life are the heater which heats the cathode, the metal-ceramic seals which must maintain a near-perfect vacuum, and the focusing structure which must assure maximum beam transmission.

Key factors influencing cathode, heater and metal-ceramic seal design

An idealized curve of cathode current versus cathode temperature is shown in Figure 2. The region to the left of the knee is known as the temperature limited emission region. The region to the right, the area where tubes are normally operated, is the space charge limited emission region. Typically, in long-life TWTs, some finite margin should exist between operating temperature and knee temperature. Another characteristic of long-life TWTs is that the cathode-knee temperature is relatively low and is stable as a function of time after initial processing. A method for measuring this parameter, known as cathode activity test, is one which provides a monitor of cathode current as a function of time after removal of heater voltage while maintaining all other voltages applied to the tube. The time-to-knee in Figure 3 is directly related to the knee temperature through the thermal properties of the overall cathode structure. This curve is taken periodically during the TWT and TWTA burn-in period to assess the quality of the cathode. The time-to-knee must be stable during final burn-in hours to assure a long-life device.

Heaters

The heater, which is the hottest element in the TWT, must provide the necessary heat to maintain the correct cathode temperature. For these reasons, the selection of reliable high-temperature materials and the limiting of the maximum heater temperature through optimum thermal design are necessary design factors in obtaining a reliable, long-life heater design. It should also be noted that during turn-on and turn-off cycles, the heater must go through a change in mechanical dimensions. The design must provide for this expansion and contraction without overstressing the heater wire or heater coating.

Metal-ceramic seals

The required vacuum environment for the cathode can be affected in several ways which tend to increase the pressure and impair cathode operation. Among these are a leak in the vacuum envelope, internal outgassing due to overheating or arcing with attendant poisoning and/or ion bombardment of the cathode. The incidence of vacuum envelope leaks is kept extremely low by use of good design, proven reliable metal-ceramic joining techniques, and very high quality materials. Careful analysis, together with thorough thermal design and testing, leads to conservatively low operating temperatures within the TWT. Under these circumstances, the TWT bakeout temperature is never approached (except at the cathode) in normal specified tube operation. Hence, the cleaning and outgassing function of bakeout is not sacrificed. A getter provides pumping capacity over extended life. Screening and storage tests are performed during the manufacture cycle to eliminate any possible leakers.

Beam focusing

With space TWTs, focusing is accomplished with periodic-permanent magnets (PPM). There are three types of material which are used in space tubes — platinum cobalt, Alnico-8, and more recently, samarium cobalt. These types of material have been chosen so that maximum magnetic field may be achieved during testing by varying the magnetic field with shunts positioned on the outside of the magnetic stack.

Let's examine the critical design parameters

The primary design parameters which differ according to the different applications are frequency, power level, gain, bandwidth and life. Secondary considerations which must be taken into account to achieve the best trade-offs for a specific application are efficiency, linearity, size and weight.

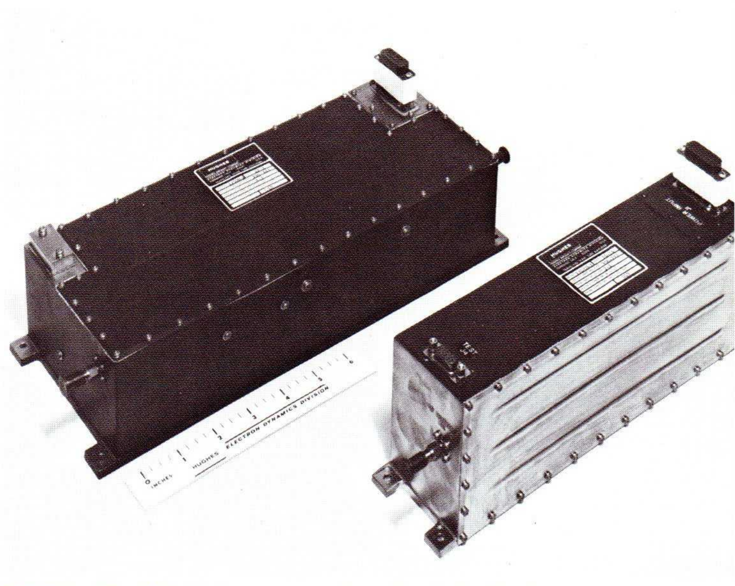


Figure 1 10 year's life is a reasonable estimate for Hughes TWTAs used in space applications.

Efficiency

An important method of reducing power consumption is by depressing the collector voltage. This is done by introducing a power supply between collector and cathode allowing for the electron beam to be collected at some value less than the full cathode voltage thereby improving efficiency. The maximum amount of collector depression and corresponding power savings is limited by the velocity spread of the spent beam at the output of the slow-wave structure.

Additional power savings may be accomplished with a multistage-depressed collector. There are limitations to the number of collectors that may be used for power savings. Power saving improvement diminishes very rapidly with more than three collector stages. The amount of power saved with additional (more than three) collectors is not practical, in most cases, due to the added complexity of the power supply.

The design analysis of multistage collectors is elaborate and critical. Hughes has developed and perfected an accurate large RF signal computer analysis and an electron trajectory computer analysis. Figure 4 shows an example of efficiency versus design voltage for a typical space-type TWT.

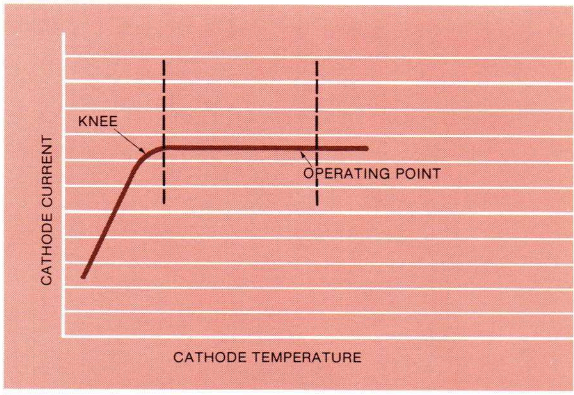


Figure 2 The region to the left of the knee is the temperature limited emission region, to the right is the space-charge-limited emission region.

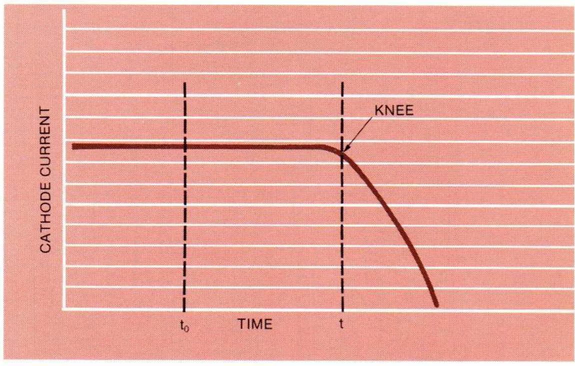


Figure 3 A cathode activity test is used to assure that the cathode-knee temperature is relatively low and stable after initial processing.

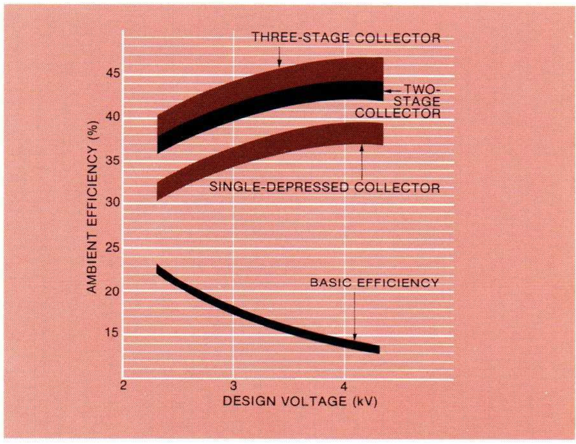


Figure 4 Hughes has perfected an accurate RF signal computer analysis and an electron trajectory computer analysis. Here's an example of efficiency versus design voltage for a typical space-type TWT.

Multistage collectors also offer the advantage of substantial power savings during small signal operation or without RF drive. This, in turn, offers a near constant thermal load, as shown in Figure 5, for a 10 watt device.

Another area that has a direct relationship to efficiency is overvoltage; i.e., that amount of voltage above the cathode voltage that corresponds to the maximum small-signal gain. The cathode voltage that determines the electron-beam velocity, however, has a strong effect on the linearity of the device. As a result, a tradeoff must be made for efficiency versus linearity. The relationship between a typical 20 watt TWT is shown in Figure 6.

In addition to these techniques, there are other methods that may be used individually or in conjunction to improve efficiency, such as velocity taper and voltage jump to resynchronize the beam and the circuit wave at large signal levels. The velocity taper method achieves resynchronization by reducing the circuit phase velocity along the axis at the same rate as the average beam velocity as shown schematically in Figure 7. The voltage jump method reaccelerates the beam near the output end of the TWT. A practical drawback of the voltage-jump method is that an additional electrode and supply voltage is required. The helix jump section must also be electrically insulated from both the RF input and output by dc blocks. Figure 8 schematically illustrates the complexity of the voltage jump method.

Bandwidth

In narrowband applications, and where AM/PM and intermodulation (IM) distortion are of little consequence, maximum efficiency can be achieved. However, this is not the case for a communications application where maximum bandwidth is required with a minimum amount of distortion. The TWT is inherently a broadband device. Figure 9 illustrates the gain-bandwidth/power-efficiency tradeoff.

Lets define TWT distortion characteristics

The following characteristics describe various forms of TWT distortion:

Phase shift

This is a measure of phase shift from RF input to RF output. Usually the total phase shift through the TWT at a given input drive is of little consequence. However, when the input drive is varied from no drive to saturation, the rate of phase shift increases and then decreases as the tube is driven into saturation. A typical power output and relative phase shift characteristic is shown in Figure 1 on page 29. In addition, over voltaging of a TWT also increases the phase shift.

AM/PM conversion

The phase shift curve slope in Fig. 1 on page 29 is the AM/PM conversion and is plotted versus RF drive in Figure 2 on page 29. The peak AM/PM conversion generally occurs at a drive level of 5 to 10 dB below saturation in the case of single-carrier operation. In the case of two or more carriers, transfer takes place giving PM at the output on one carrier due to AM at the input on the other.

Noise figure

The noise figure is a measure of the degradation in signal-to-noise ratio with passage of the signal through the tube. For medium power C-band tubes, the noise figure is typically 30 dB. This figure increases as power and frequencies increase.

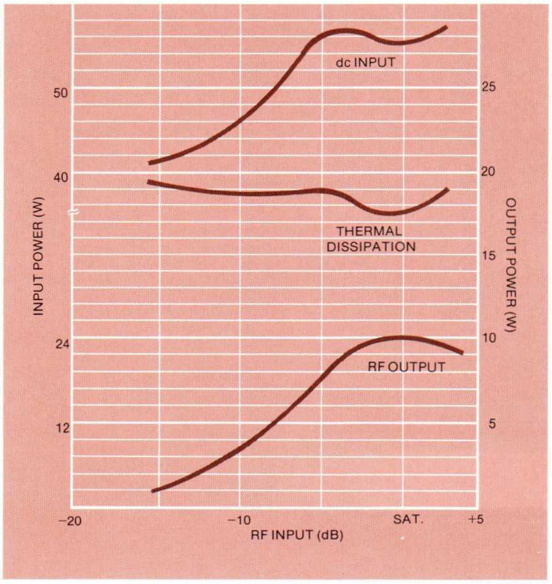


Figure 5 Multi-stage collectors offer substantial power savings during small-signal operation or without RF drive, resulting in a near constant thermal load.

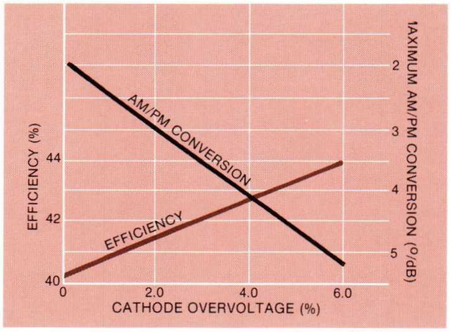


Figure 6 Since cathode over voltage directly affects efficiency in a TWT, it is important to describe the relationship between these parameters and third-order intermodulation.

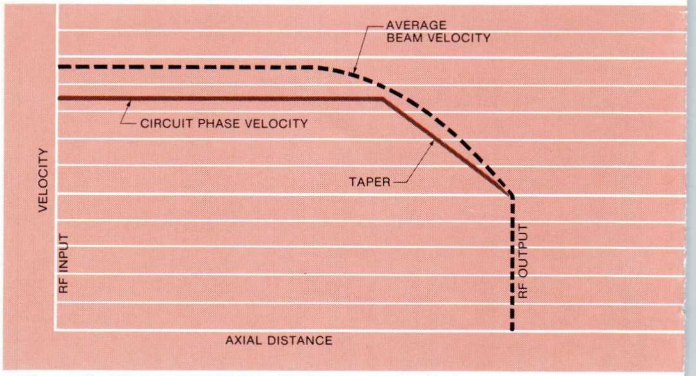


Figure 7 To improve TWT efficiency, a velocity taper scheme resynchronizes the beam.

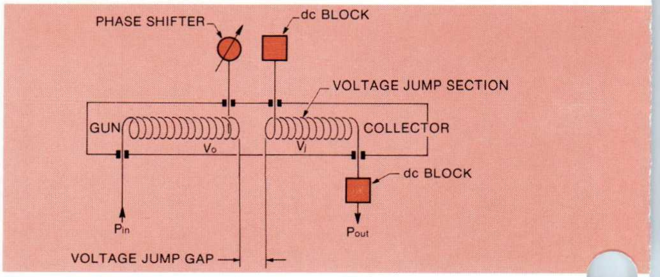


Figure 8 Another method to improve TWT efficiency is the voltage jump which reaccelerates the beam near the output end of the TWT.

Intermodulation distortion (IM)

Since TWTs are inherently broadband devices, they can be used to amplify more than one carrier due to the instantaneous bandwidth characteristic. When more than one carrier is introduced into the tube, a mixing, or IM process, takes place. This results in IM products which are displaced from the carriers at multiples of the "difference" frequency. The power levels of these IM products are dependent on the relative power levels of the carriers and the efficiency of the tube. Figure 7 on page 30 shows, with two balanced carriers, the variation of carrier and product power level with total drive power. The single carrier power curve is plotted for comparison. The IM distortion is significantly reduced in the small-signal (linear) region.

Harmonic power

Due to the wide bandwidth of the TWT, the output spectrum generally contains harmonic power. The second harmonic, when the tube is operated at saturation, is typically 8 to 10 dB below the fundamental. Other higher order harmonics are present, but to a much lesser degree. The harmonics are a function of frequency and will decrease as frequency increases.

Time delay/group delay

As with any device that has physical length, the TWT has an associated time or group delay which is a measure of the time it takes for information to travel from input to output. Typically, this delay is 10 nanoseconds or less. Distortion only results if the delay is not a constant function of frequency. The broadband helix tube inherently shows little gross change in time delay across the typical 10% communication bandwidths, but will have some fine grain ripple which is typically less than 1.5 nanoseconds. The ripple magnitude is held to a minimum by careful attention to internal mismatches in the TWT.

Gain variations

Slight fluctuations in small-signal gain when frequency is varied are termed fine-grain or fine-structure variations. These variations are due to internal reflections caused by mismatches in the TWT. The reflected signal is amplified and as it travels back, may add or subtract from the input signal, thereby causing gain variation. Figure 5, on page 29, is a typical plot of gain variation versus frequency.

How to make a ten-year life TWT

The life determining design feature of a TWTA is the cathode of the tube. Hughes, back in the late 50s, selected oxide cathodes as its source of providing electron emission for stable, long-life performance. In the years since, this has proven to have been an excellent selection, confirmed by life test as well as actual spacecraft operation.

Based on the data that Hughes has accumulated over the years, all long-life (7 to 10 year) space-type TWTs utilize oxide cathodes. To assure Hughes of long life with an oxide cathode, the loading of the cathode is usually kept below 250 mA/cm^2.

There are three life-limiting mechanisms for an oxide coated cathode—the total coating depleted, the change of mixed oxide coating stoichiometry, and the activator arrival rate. All of these mechanisms change with operational time depending on temperatures, structural dimensions, intial concentrations of activators and coatings, and the vacuum environment within the TWT. From accumulated life data, the temperature, minimum activator arrival rate, allowed coating depletion, and the limited oxide mix stoichiometry are empirically determined. The dimensions, concentrations of activators and coatings and the vacuum environ ment are controlled by well proven processes and procedures.

What determines TWT size and weight?

The TWT size is determined by the physical laws which determine the frequency response, linearity, and efficiency. The weight depends on the size, materials used, and the structural techniques employed for the necessary strength to survive the thermal stresses, pyrotechnic shock and vibrations encountered during launch and operations.

The size and weight of the electronic power conditioner (EPC) is dependent upon thermal interface, RFI and telemetry requirements, spacecraft power bus, allowable ripple current that the TWTA can inject on the power bus, residual AM and PM noise, and shock and vibration to be experienced. TWTAs may be mounted on a common baseplate or, for weight savings, mounted directly to the spacecraft platform.

The "venable converter": A new approach to voltage conversion/regulation

The EPC converts the regulated or unregulated spacecraft bus voltage to the dc voltages at the proper levels and necessary regulation required to operate a given TWT. A simplified block diagram of a typical EPC is shown in Figure 10. The heart of the EPC is the new approach to voltage conversion and regulation known as the "Venable Converter" patented by Hughes*. This converter utilizes a circuit configuration that achieves such desirable features as higher efficiency, a single circuit for regulation and conversion, minimized output filter requirements, and simplified control system applications.

Hughes has developed and manufactured EPCs for tubes capable of 200 mW to 100 W of CW power. These units range in cathode voltage from 1,200 to 5,000 volts and will operate from a regulated or unregulated bus. In addition, EPCs have been developed for pulsed applications with cathode voltages in excess of 10,000 volts.

*U.S. patent no. 3,025,715

Hughes has ongoing programs exploring efficiency improvements, longer life and reliability, packaging techniques, the effects of radiation, multistage collector operation, and system interface as it relates to both thermal and the power bus of the spacecraft.

An added benefit of developing and manufacturing the EPC and TWT within the same organization is that it offers design flexibility wherein the TWT and EPC engineer can work closely in resolving complex interface problems between TWT and EPC. This provides for an optimum TWTA design.

Space TWT and TWTA experience

At Hughes, L- through Ku-band TWTs and TWTAs have been life tested in excess of five-million hours. Table 1 lists some of the TWTs and TWTAs which have accumulated a significant number of these hours.

The saturated RF output power and small signal gain has been monitored during the life testing of Hughes Model 1200H and 1202H TWTAs. Figure 11 is a plot of RF output power and small-signal gain versus time on one of the 1202Hs on life test, which is typical for all the units on test.

In addition to these operating tests, Hughes has performed other tests to establish life and reliability such as storage, on/off cycles, cold starts, elevated temperatures, etc.

Hughes TWTs and TWTAs in space are approaching 10-million hours of operation. In Table II, some of the TWTs and TWTAs which have accumulated a significant number of hours are listed.

What's new in the future for space TWTs/TWTAs?

The future trends being dictated by systems requirements are toward higher frequency, greater efficiency, better reliability, longer life, smaller size, lighter weight and, in some cases, higher power.

The migration to higher frequency, from a tube standpoint, will make a smaller and lighter device. However, as the frequency increases, cathode voltages usually increase causing the EPC to grow in both size and weight. This, in turn, will force the investigation, qualification, and, in some instances, development of new materials and processes.

Table I Accumulated TWT/TWTA life test hours

SPACECRAFT	TUBE TYPE	NO. OF TUBES	TOTAL HOURS
Syncom	314H	9	810,345
Surveyor	349H	8	272,060
ATS	384H	12	812,379
ATS	384HA	13	507,031
Early Bird	215H	8	162,098
TACSAT	240H	2	119,429
DSCS-II			
1200H	263H	6	311,038
1202H	265H	6	261,865

Table II Accumulated space operation of some typical TWTs and TWTAs

SPACECRAFT	TUBE TYPE	NO. OF TUBES	TOTAL HOURS
Pioneer	214H	8	343,927
Intelsat III	233H	10	415,700
Intelsat III	235H	10	415,700
Intelsat IV	261H	168	3,000,960
Westar	275H	24	569,080
Canadian Domestic	275H	36	940,200
RCA Satcom			
1288H	296H	48	390,144
Data Systems	837H	17	498,396
DSCS-II			
1200H	263H	16	110,268
1202H	265H	16	138,030
NATO-III			
1240H	265HA	8	41,672

The future improvements in efficiency will be gradual as the TWT and EPC approach maturity. Efforts will be continuing in resynchronization and multistage collector techniques for TWT efficiency improvements, while new circuit techniques will be explored and new components evaluated for efficiency improvements in the EPC.

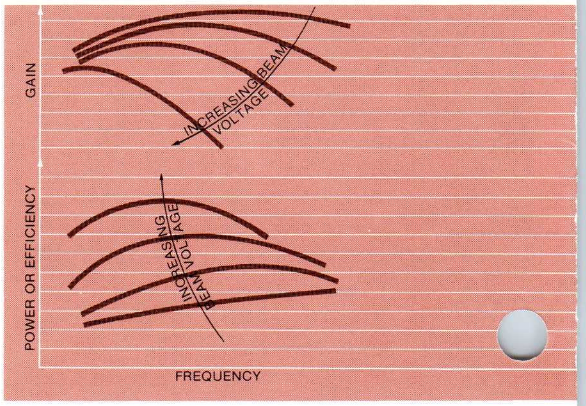
Higher reliability can be achieved by additional screening, testing and burn-in. This is usually a trade off of time (schedule) and cost.

Longer life may be brought about by lower cathode loading, incorporating into future designs the experience gained through life testing and actual system usage, and a continuous program of cathode material improvement and evaluation.

The smaller size and lighter weight will come about by exploring and developing new materials, more efficient ways to package the EPC, improved techniques of heat removal, and working in close relationship with system engineering so that a given TWT/TWTA is not over designed or over specified.

Higher power TWTs/TWTAs have been developed and manufactured for other applications. Therefore, it will require the transfer of that technology to space hardware while still maintaining and assuring the constringent requirements needed for such hardware.

Figure 9 Tradeoffs between gain and efficiency are possible as bandwidth requirements change in system designs.



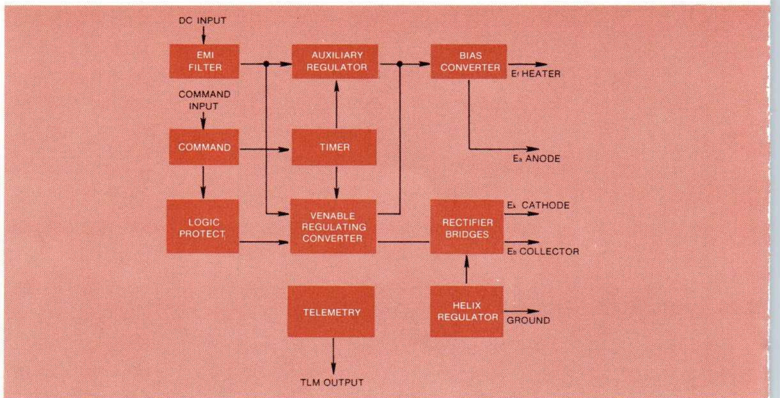
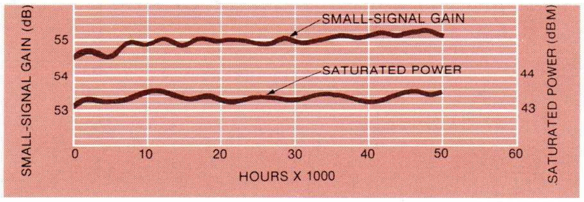


Figure 10 The heart of the EPC is the new approach to voltage conversion and regulation known as the "venable convertor"

Figure 11 Typical results of RF output power and small-signal gain versus time for Hughes 1202H TWTA.



TWTs and TWTAs: Ideal for communications systems

Microwave communication system developments, both terrestial and satellite, have produced needs for RF power amplifiers with greatly improved reliability and performance characteristics. Amplifiers with higher output power, greater efficiency, increased instantaneous bandwidth, less signal distortion, reduced cooling requirements and longer operating life are needed to meet the performance and cost objectives of these systems. To keep pace with these new requirements, Hughes Electron Dynamics Division has developed a new series of low and high power communications amplifiers and TWTs for commercial and military applications.

There's quite a selection of low-power amplifiers (LPAs)

Hughes 9000H Series of Communications Amplifiers are specifically configured for use as intermediate power amplifiers in large satellite earth terminal transmitters and as output amplifiers in small-capacity terminals. As shown in Figure 1, each unit is completely self-contained and consists of a periodic permanent magnet (PPM) focused TWT, solid-state power supply, integral cooling and protective circuitry. Optional RF features include: solid-state driver for increased gain, output isolator for TWT protection, bandpass filter, output power monitor (front-panel meter or remote indicator), input isolator, and input adjustable attenuator. This power amplifier series uses any of several rugged metal-ceramic TWTs derived from Hughes' space qualified devices to provide 10 to 50 watts of RF power output in the 6 and 14 GHz satellite up-link bands.

The solid-state power supply offers optimum interface with the TWT for proven reliability and tube protection.

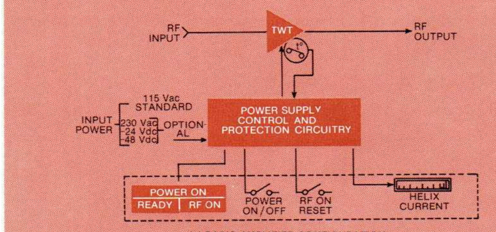
Power consumption is held to a minimum. Protective features include excess helix current overload, thermal overload and automatic time delay for tube warm-up. Other available features associated with the power supply are: high-voltage interlocks, operation from 115 Vac, 230 Vac, 48 Vdc or 24 Vdc input power, remote controls/status indicators for remote operation, and redundant power amplifier operation.

These compact, lightweight units are particularly suited for transportation to remote sites. They can be mounted in a 19-inch rack with a panel height of 3-1/2 inches and a maximum depth of 20 inches.

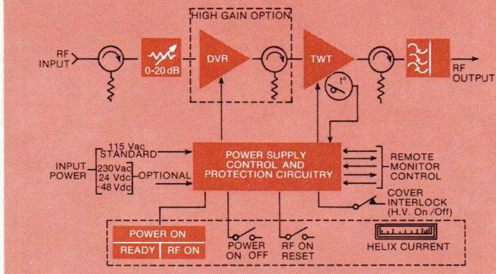
9000H Series Amplifiers are available in a basic configuration including a power supply, TWT and control/protection circuitry, or as a complete power amplifier including optional features, as shown in Figure 2.

In addition, a redundant control unit, shown schematically in Figure 3, is available to provide control for the redundant operation of two low-power or high-power amplifiers in the 9000H Series.

Figure 1 This Hughes communications power amplifier is self-contained and includes a PPM-focused TWT and solid-state power supply with integral cooling and protective circuitry.



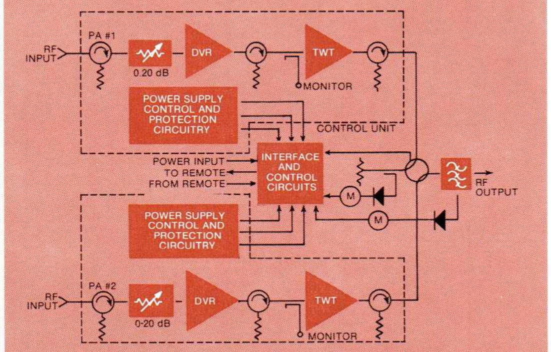
(a) BASIC AMPLIFIER CONFIGURATION



(b) POWER AMPLIFIER CONFIGURATION

Figure 2 The 9000H Series Amplifiers are available in (a) a basic configuration with power supply, TWT and control/protection circuitry or (b) as a complete power amplifier including optional features shown.

Figure 3 Where necessary, a redundant control unit is available to operate two low- or high-power amplifiers in the 9000 H Series.



REDUNDANT CONFIGURATION

300 and 600 W high-power amplifiers (HPAs) also available

Hughes offers complete HPAs both at 300 W and 600 W. These units are identified as 9240H02 and 9360H04. These HPAs offer a wide variety of features which make them a suitable subsystem for all communications applications. The 9240H02 is composed of two parts, as shown in Figure 4, which consist of the RF drawer and power-supply drawer.

Unique designs produce flat gain response high-power coupled-cavity TWTs.

High power coupled-cavity TWTs have been developed by Hughes to meet requirements of 400 W to 14 kW communications ground terminal power amplifier applications by applying special techniques to increase tube performance and reliability characteristics.

Typical of these TWTs is the Hughes Model 792H which was developed for use as the final power amplifier in the FSC-78 military satellite communications ground stations. It operates over the 7.90 to 8.40 GHz frequency range, producing up to 5 kW of RF output power. For such communication systems, low distortion is required at all output power levels since the overall system performance is, in large part, determined by the output TWTs performance. Extremely low amplitude and phase ripple is achieved by means of special tube construction techniques and an integral gain equalizer.

Other tubes designed for these applications include the 8760H which provides up to 1.2 kW of CW power in the 7.9 to 8.4 GHz band and the 876H providing 600 to 700 W of CW power at 14.0 to 14.5 GHz. Both tubes are PPM focused and air cooled. In the area of higher power tubes, the 870H provides 5 kW of CW power in the 14.0 to 14.5 GHz band and the 8723H 14 kW in the 7.9 to 8.4 GHz band. Both tubes are solenoid focused and liquid cooled.

Special emphasis on minimizing gain and phase variations is given in the design of the circuits for these tubes. Gain and phase variations result from feedback caused by mismatches in the circuit sections. The principal mismatches occur at the ends of the sections; i.e., the internal terminations and the input and output RF waveguide couplers. The larger the mismatches at these points and the higher the gain in each circuit section, the greater the gain and phase variations.

The internal terminations normally used in coupled-cavity circuits are of relatively short electrical length, being confined to a single cavity. As a result, the mismatch of these terminations can be reduced to a low but imperfect level. Hughes has developed and patented a tapered internal termination* for coupled-cavity circuits that extends over several cavities. The long electrical length of this termination and the gradually tapering loss patern results in a very low mismatch. This technique also introduces in-band loss in the section, further reducing the feedback effect. The tapered loss is achieved by using small cavities adjacent to the circuit cavity. These cavities are loaded with lossy ceramic "buttons" that protrude significantly into the cavity. The protrusion, or reentrancy, of a button determines the amount of in-band loss; the amount of loss is easily tapered in successive cavities by simply changing the amount of button reentrancy as illustrated in Figure 5.

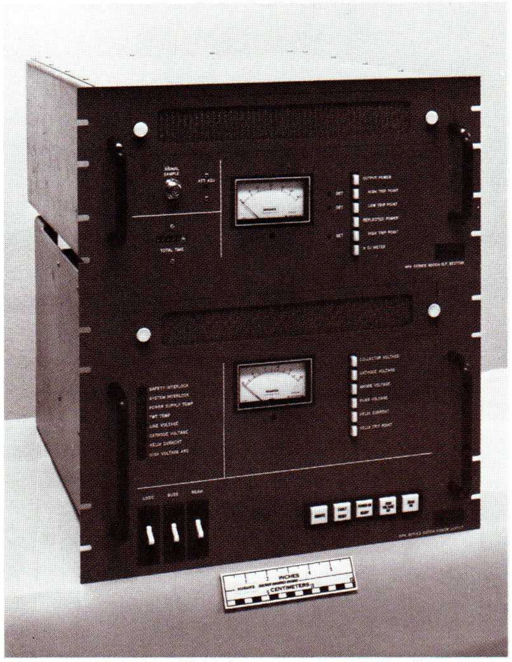


Figure 4 This 300 W high-power communications amplifier (9240H02) consists of an RF drawer and a power-supply drawer.

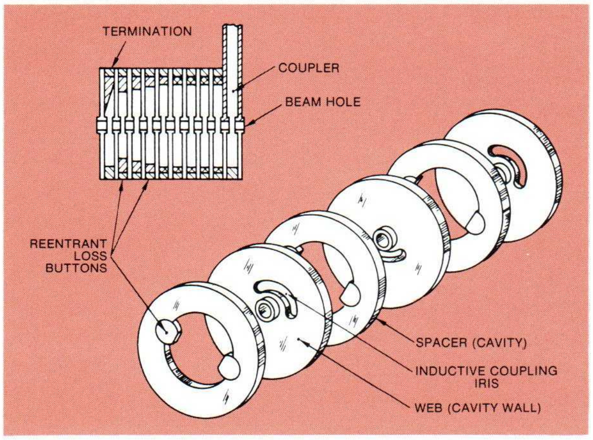


Figure 5 In the Hughes patented coupled-cavity slow-wave circuit, lossy ceramic buttons are used to produce a gradually tapering loss pattern to reduce mismatch between internal terminations and the input and output RF waveguide couplers.

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*U.S. patent no. 3,181,023

The utilization of the techniques discussed produces a TWT gain response with very little amplitude ripple. A comparison in Figure 6 of the small-signal gain variation of the 792H with a typical coupled-cavity radar tube indicates the smooth parabolic characteristic that is achieved.

To obtain the desired constant amplitude response, a simple single-pole external gain equalizer is used. By adjusting the transmission loss of the equalizer to be the inverse of the TWT gain-frequency curve, the overall variation is reduced below 0.60 dB across the operating band. Typical 792H characteristics are shown in Figure 7 for three output power levels — 0, 10 and 20 dB down from saturation. Maximum amplitude variations over 40-, 125- and 500-MHz bands are 0.30 dB, 0.40 dB, and 0.60 dB, respectively.

Use of an external equalizer also improves the tube's phase linearity characteristics. Figure 8 shows the phase linearity versus frequency at 10 dB below saturation. The maximum phase deviations in the 40 MHz and 125 MHz bands are 1.0 degrees and 2.0 degrees, respectively. The coincident improvement of both amplitude and phase characteristics with a single external equalizer is due to the fact that both variations result from the mismatches within the TWT. The simplicity of the equalizer makes it relatively insensitive to external influences, such as coolant temperature fluctuations or source and load VSWR.

The performance achieved on the 792H is not unique; similar characteristics have been achieved with other Hughes TWTs.

Coupled-cavity TWT amplifiers headed for 100 GHz

In the future, coupled-cavity TWT developments will result in CW communications amplifiers at frequencies up to 100 GHz and increased output power levels. High efficiency resynchronization and multistage collector depression techniques will be applied to many more TWT designs to save energy and minimize cooling requirements. TWT efficiencies will continue to be increased to levels that, in the past, could only be achieved by narrowband kystron amplifiers. The use of multistage collectors will be particularly effective in tubes for multicarrier amplification where operation at reduced output power levels (and hence, reduced basic efficiency) is necessary for low intermodulation products. Efficiencies of 25% or greater are achievable objectives.

The recent developments in high-energy, rare-earth magnetic materials and heat pipe technology have made possible PPM-focused, air-cooled, coupled-cavity TWTs producing greater than one kilowatt of RF output power in the I- and J-bands. Such tubes can put inexpensive, transportable ground terminals within reach.

Further reductions in high-power TWT amplitude and phase variations with frequency will be achieved as matching and equalization techniques are refined. Methods of linearizing the tube input/output transfer characteristic to permit reduction of intermodulation products near saturation are also being investigated. These developments will continue to improve the performance characteristics of high-power coupled-cavity TWTs and the communications systems in which they are used.

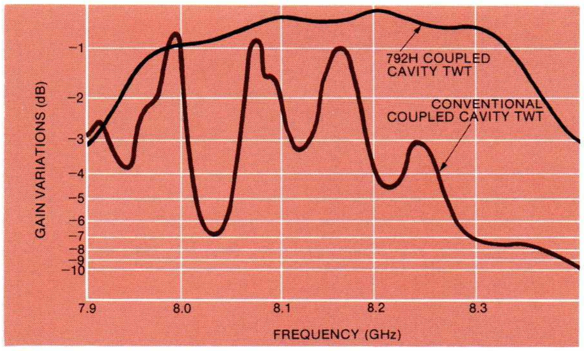


Figure 6 Very little amplitude ripple in gain response occurs with a 792H coupled-cavity TWT compared with a conventional coupled-cavity tube.

Figure 7 By adjusting the transmission loss of an external gain equalizer to be the reverse of the TWT gain-frequency curve, a flat overall gain response is achieved over a wide bandwidth.

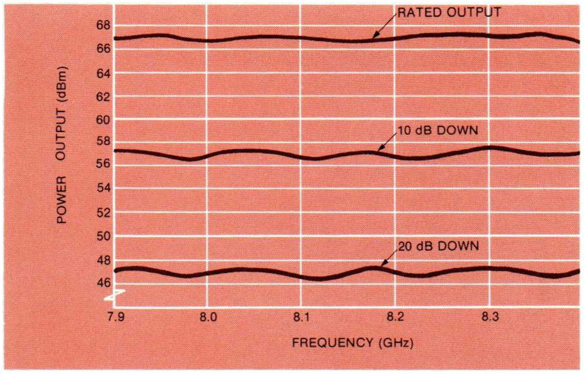
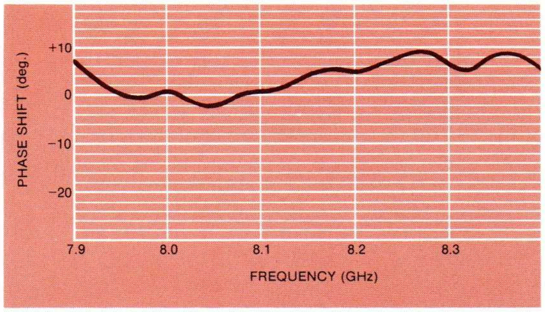


Figure 8 The phase linearity of the 792H is also improved by the external equalizer.



For high-power protection … try multipacting

Transmit-receive (TR) limiters serve two basic functions. First, they attenuate power entering the receiver during a transmitted pulse to a level which will not harm the receiver or bias it to a temporarily insensitive condition. Second, during receiver on-time, the limiter provides a path of minimum insertion loss, subjecting the receiver to the strongest possible return signal.

Over the last several years, a number of high pulsed repetition frequency radar systems have evolved which require a TR-limiter system that can handle powers on the order of 50 kilowatts, yet display insertion losses of about 0.5 dB and recovery times of less than 5 nanoseconds. This very short recovery time allows monitoring the maximum possible return signal. The Hughes multipactor shown in Figure 1 takes advantage of the principle of multipacting (multiple impacting) to meet these demanding specifications.

Figure 2 shows the relative location of a multipactor TR limiter system in a simplified radar block diagram. The protective circuit consists of a high-power stage (multipactor) which limits the power to several watts, and a low power stage (solid-state limiter) which further reduces the power to milliwatts.

Basically, the multipactor section offers protection against three potentially dangerous situations: (1) sharp pulses due to mis-matches, (2) high-power arcing at the antenna, (3) the presence of extraneous radar signals.

When the transmitter is on, up to 10% of the transmitted power (50 kW peak) can be reflected due to the impedance mismatch of the antenna. Thus, the multipactor is normally required to limit approximately 5 kW of reflected power to about 8 watts. A more serious limiting problem can occur during transmitter on-time if a high-power arc should develop at the antenna. In this case, up to 80% reflection can occur and the multipactor section must attenuate approximately 40 kW down to 8 watts. In both cases, the limited power is absorbed by the multipacting process and the resulting heat is removed by conduction cooling.

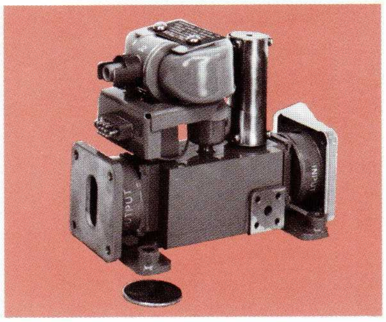
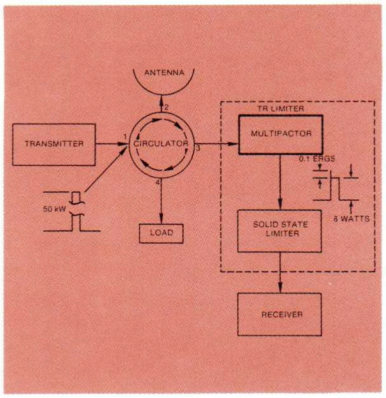


Figure 1 Actually a small system, the multipactor limiter requires electron and oxygen sources as well as an ion pump.

Figure 2 Multipactor limiters handle up to 50 kW peak power at X-band.



A third limiting process occurs when extraneous radar signals are present. The RF circuit of the multipactor essentially constitutes a bandpass filter. Since the operating band of the multipactor is coincidental with the passband, any out-of-band signals received by the antenna will be reflected and absorbed at port four of the circulator by the dummy load. The multipactor section of the limiter requires no synchronous signal for operation. The first half cycle of the incident RF wave initiates the multipacting process.

Confused about TWT terminology? They are clarified in this glossary of terms

AM/PM conversion (amplitude modulation/phase modulation) is defined as the change in phase angle between input and output signal as the input signal level varies. Ths factor is measured dynamically and is expressed in degrees per dB at a specified value of power output.

AM/PM conversion in a TWT is due to the reduction in beam velocity as the input signal level increases, causing a greater energy exchange between the beam and the input RF wave. At levels 20 dB below the input required for saturation, AM/PM conversion is negligible. Beyond this point, AM/PM conversion increases sharply and phase actually reverses when the TWT is driven well beyond saturation.

A typical power output and relative phase shift characteristic is shown in Figure 1 for a TWT operated as a wide-band, low-distortion amplifier. Here it is seen that phase shift is relatively insensitive to drive in the small signal ("linear") portion of the RF output power characteristics. As the TWT is driven into saturation, the rate of phase change increases and then decreases as the output power saturates. The slope of this line, or AM/PM conversion, is plotted against RF drive in Figure 2. The peak AM/PM generally occurs at a drive level 3 to 10 dB below saturation drive and is frequency dependent. The value of AM/PM conversion is less at the low frequency end of the tube's passband than at the high frequency end. These data apply in the case of a single carrier. For two or more carriers, transfer takes place giving PM at the output on one carrier due to AM at the input on the other. The general trend with drive is similar for this case, but the specific values are different and are also a complicated function of the relative carrier amplitudes.

Dynamic range refers to the variation between the highest and lowest signal levels that can be amplified linearly; linearity defined as the point where further increase in input produces 1 dB of gain compression. Generally, the smallest input level that can be handled is determined by the TWT noise figure and effective bandwidth. The maximum input level is set by the point at which saturated power output is exceeded. A wide dynamic range TWT offers a low noise figure and a relatively high power output before saturation is reached. Typical values of dynamic range are tabulated as:

Dynamic Range (dB) =

$$10 \log \left(\frac{P_{in}}{1 \text{ mW}} \right) - \left[10 \log \frac{(kTB)}{(1 \text{ mW})} + NF \right]$$

where P_{in} = RF input (mW) to produce max. undistorted RF output

kTB = standard noise power (mW)
k = Boltzmann's constant (1.38×10^{-23})
T = standard temperature (290° K)
B = standard bandwidth (1 MHz)

$$10 \log \left(\frac{kTB}{1 \text{ mW}} \right) = -114 \text{ dB}$$

Efficiency is generally defined as that portion (percentage) of the maximum total primary input power that is converted to RF output power. Various techniques can be employed on TWTs to increase efficiency. These range from velocity resychronization of the electron beam with the slow-wave structure to multiple stage collectors. Employing such techniques, efficiencies in excess of 50 percent have been obtained.

Gain is defined as the ratio of power output to power input and generally expressed in decibels (dB) as:

$$\text{Gain (dB)} = 10 \log^{10} \frac{P_{out}}{P_{in}}$$

With TWTs, gain is not a simple figure. Frequency, output power beam voltage, and helix velocity all determine the gain figure. For a particular frequency, and at specified electrode voltages, a curve displaying gain and output power versus input power for a TWT can be illustrated as in Figure 3. As shown, gain is relatively flat in the low-level input region and this value is termed the small-signal gain. As input power increases, output power reaches a maximum, called saturated power output, and gain is termed saturated gain. Saturated gain is normally 6 to 8 dB less than small-signal gain. The three characteristics (small-signal gain, saturation gain and saturation power output) are shown in Figure 4 for an octave band helix tube.

A typical octave band TWT may display slight fluctuations in small-signal gain when frequency is varied, as shown in exaggerated form in Figure 5. Such variations are termed fine grain or fine structure and are due to internal reflections caused by mismatches in the tube structure. The reflected signal is amplified and, as it travels back, may add to or subtract from the input signal.

Harmonics, or signals at multiples of the fundamental frequency, are generated due to the non-linearity of TWTs. When a tube is operated well below saturation in the small-signal area, harmonics are relatively nil. However, when a TWT is driven to saturation and operates in its non-linear region, harmonic content rises sharply and the harmonic power can actually equal or even exceed the fundamental power.

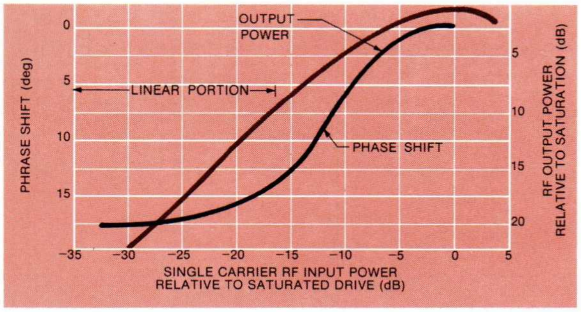
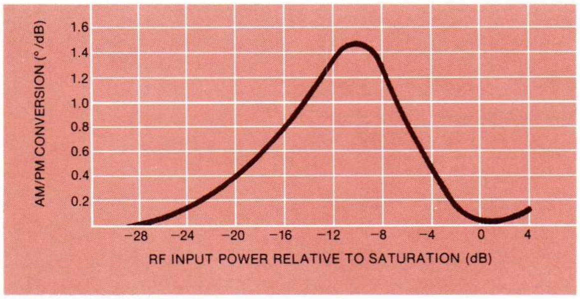


Figure 1 Typical power output and phase shift as a function of RF input power for a communications type TWT.

Figure 2 For a single carrier condition, AM/PM conversion rises sharply as drive is increased.



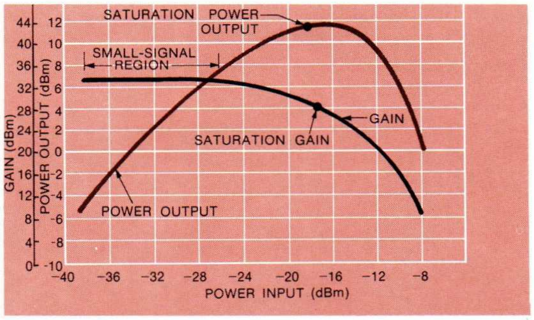


Figure 3 Gain and output power versus input power for TWT operation at one frequency.

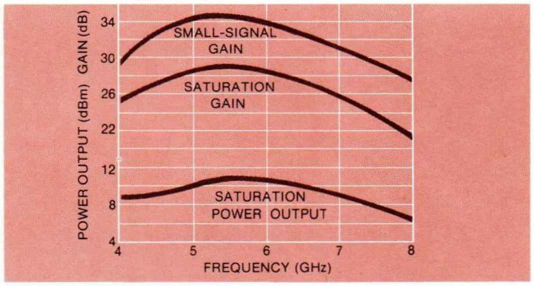
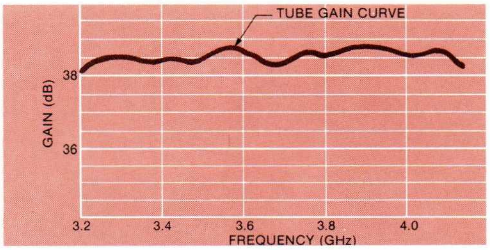


Figure 4 Small-Signal gain, saturation gain and saturation power output plotted against frequency.

Figure 5 Fine-grain or fine structure variations in small-signal gain are caused by mismatches in the TWT tube structure.



Because of the wide bandwidth of helix-type TWTs, the output spectrum generally contains some harmonic power. Figure 6 shows the variation of second harmonic power as a function of beam voltage (efficiency) with RF drive power as a parameter. This performance varies with frequency so that the harmonics of the upper-band-edge fundamentals are lower than those of the lower-band-edge fundamental drive signals. With coupled-cavity tubes, additional rejection of the harmonics is obtained by virtue of the natural selectivity of the circuit. The second harmonic is typically 20 to 30 dB below the fundamental in these tubes.

Intermodulation distortion. When more than one carrier is introduced at the TWT input, a mixing, or intermodulation (IM) process, takes place. This results in intermodulation products which are displaced from the carriers at multiples of the difference frequency. The power levels of these intermodulation products are dependent on the relative power levels of the carriers and the efficiency of the TWT. In the case of two balanced carriers, Figure 7 shows the variation of carrier and IM product power level with total drive power. The single carrier power curve is also plotted for comparison. As was the case with AM/PM conversion, the IM distortion is significantly reduced in the small-signal (linear) region of the RF drive range. For this reason, communication TWTs are normally operable well below their saturation power level.

Noise figure is a measure of the degradation in signal-to-noise ratio with passage of the signal through the TWT. It is defined as the ratio of the signal-to-noise power ratio (S/N) at the input of the TWT to that at the output or:

$$NF = \frac{(S/N)\ \text{in}}{(S/N)\ \text{out}}$$

Noise in a TWT is produced by shot noise or current density variations as electrons leave the cathode surface and velocity fluctuations of the emitted electrons. For low-noise TWTs, the spacing of the electron gun relative to the helix is critical. The various electrode voltages are also specified to offer an optimum potential profile for the gun structure.

Low-noise traveling wave tube amplifiers offer noise figures less than 10 dB. For medium power satellite TWTs, noise figures range from 18 to 30 dB. Typically communications satellite transponder output TWTs offer 24 to 27 dB noise figures with driver TWTs exhibiting noise figures from 16 to 23 dB. These values increase as frequency and power levels rise. Coupled-cavity tubes, for example, typically have noise figures of 35 to 40 dB.

Over-drive capability of a TWT indicates the range over which the output power will remain in the saturation region as input is increased. In a standard tube design, as input is increased output rises until saturation is reached. When further input is applied, output power decreases. For certain applications, it is desirable to maintain full or saturated power output over a broad range of input signal conditions. Limiter action to achieve this objective is in the design of the RF structure, use of multiple attenuators and cascading two TWTs with additional equalizers and isolation filters.

Serrodyning is a modulating technique whereby a periodic sawtooth voltage applied to the TWT helix causes a frequency shift of the input to output signal. This approach for frequency conversion is applicable for Doppler radar and ECM when a fixed or constant rate change of signal is desired.

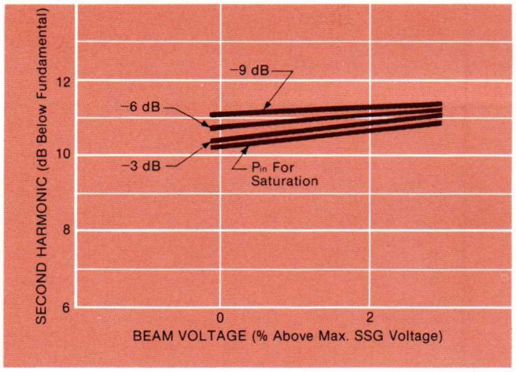
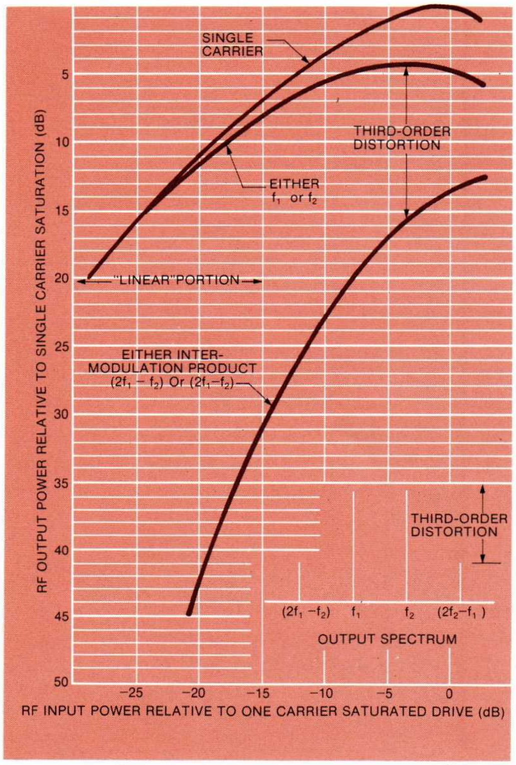


Figure 6 Harmonic power versus beam overvoltage for an X-band space TWT.

Figure 7 Typical third-order intermodulation data for Intelsat IV type TWT.



Cross Index of Models

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HUGHES
TWT AND TWTA HANDBOOK

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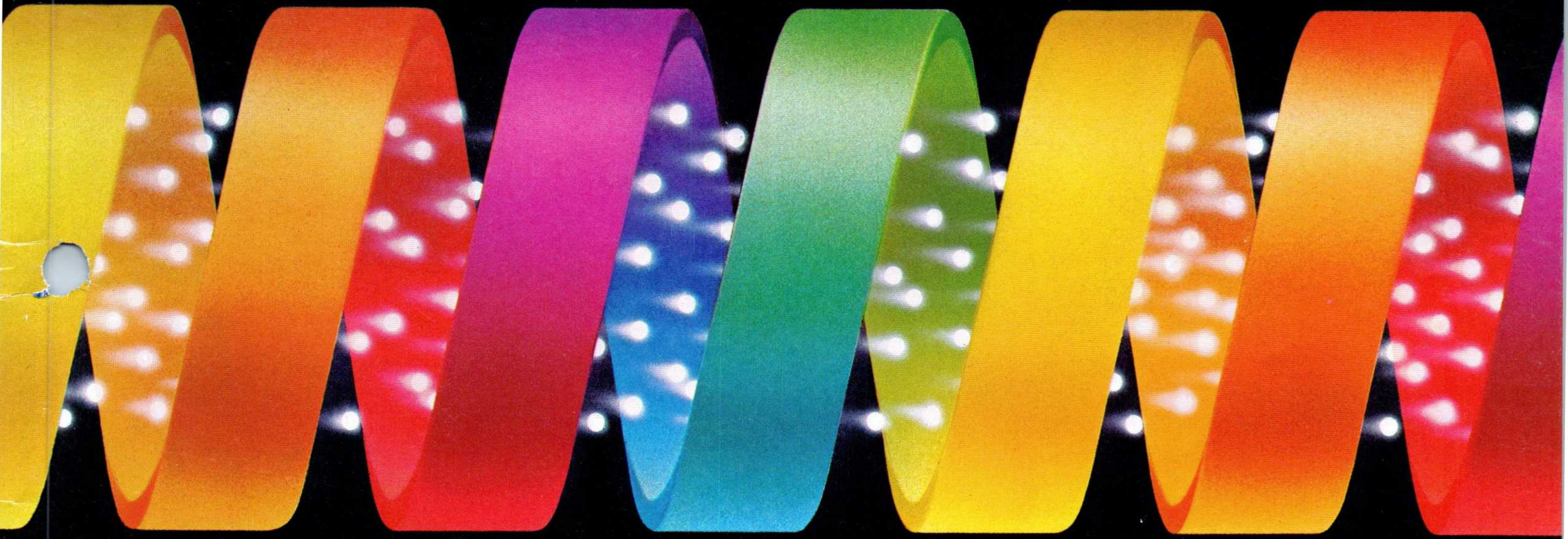

Table of Contents

Introduction to the TWT

Traveling-wave tube

Electron tube used for the generation of microwave frequency radiation or for amplification at ultra-high frequencies, the operation of which depends on the interaction of a beam of electrons with an electromagnetic wave.

The history of microwave technology is a history of progressive advances in the techniques used to generate and amplify microwave frequencies. First came the triode, at the threshold of the microwave region, followed by the magnetron and other crossed-field devices. Then the klystron, and today the traveling-wave tube (TWT).

It would be difficult to imagine present-day microwave technology *without* the TWT and TWT amplifier (TWTA). No other devices can match the TWT's unique combination of bandwidth and gain. From electronic warfare to space exploration to the relaying of home-video signals, the TWT has expanded the microwave horizon. And the Hughes organization has been at the forefront of each of these TWT developments.

The purpose of this Handbook is to present an overview of today's TWT technology and the Hughes products which can be used to implement this technology. It is, in a sense, both a history and a prophecy. It will tell you where we are, and point the way toward new TWT innovations and applications—at Hughes and in your own development laboratory.

Glossary of Terms

AM/PM conversion

A term used with microwave tubes. Defined as the "amplitude modulation/phase modulation conversion," and is the change in phase angle of the output RF voltage produced by variations in input signal level, usually expressed in degrees/dB.

Anode

1. A positively charged electrode to which the main stream of electrons flow. 2. In a gridded vacuum tube, it is called a plate. 3. In a cathode-ray tube, the anodes are connected to a positive potential source. The anodes concentrate and accelerate the electron beam for focusing.

Average power

1. A value of power equal to the time integral of the instantaneous peak power divided by the time of the integration. 2. In circuits containing reactance and resistance, the current and voltage values may, at any instant, be of the same or different polarity. Depending on this condition the instantaneous power ($E^{X}I$) will have a positive or negative sign. The average power will be the net value taken over a cycle. This net power is due to the resistance present in the circuit.

Backstreaming

A condition in which a portion of the electron beam is reflected from the collector and travels "backward" toward the electron gun. This is an undesirable effect, distorting the primary electron beam and any modulation that may be present.

Backward wave oscillator

Abbreviated BWO. A wideband voltage tunable oscillator related to a traveling-wave tube in somewhat the same way that a klystron oscillator is related to a klystron amplifier. It uses a broadband circuit similar to a TWT. Internal feedback exists because the RF energy travels in a direction opposite to that of the electron stream.

Body/helix protection

Any combination of circuit elements from a simple resistive network to a complex "crow-bar" device, designed to prevent damage to the TWT slow-wave structure as the result of arcing or unusually high intercept current.

Cathode

A negatively charged electrode which emits electrons.

Cathode loading

The current density at the emitting surface of the cathode — usually expressed in amperes per square centimeter.

Collector

1. The output element of a vacuum tube that dissipates (or collects) the unconverted energy in the electron beam as thermal energy. It performs the same function as a plate in a standard vacuum tube. 2. In a transistor, the element which "collects" the current generated at the junction between the emitter and the base. The collector is the output element in a transistor and performs the same function similar to the plate in a vacuum tube.

Contra-wound helix

A slow-wave structure where two helices, wound in opposite directions, are superimposed into a single structure. This circuit offers substantially higher power than a conventional helix with some sacrifice of bandwidth.

Control grid

An electrode mounted between the cathode and the anode of a tube to control the flow of electrons. An appropriate negative voltage (with respect to the cathode) reduces the electron flow (beam current) to zero or cut-off and an appropriate positive voltage allows current to flow. This electrode is usually some sort of mesh structure.

Coupled-cavity tube

A TWT with a slow-wave structure made up of a number of "cavities" electrically coupled by means of coupling holes or slots. This circuit is capable of very high-power operation.

Crossed-field device

A high-vacuum electron tube in which a direct, alternating or pulsed voltage is applied to produce an electric field perpendicular both to a static magnetic field and to the direction of propagation of a radio-frequency delay line. The electron beam interacts synchronously with a slow wave on the delay line.

Current density

The number of electrons per unit area. Usually expressed as amperes per square centimeter.

Depressed collector

Applying a negative potential (with respect to the tube body or "ground") to the collector to slow the electron beam velocity in the region of the tube output coupler. This provides better synchronism near the output with the result that more power can be extracted from the beam, thus, improving the conversion efficiency of the device.

Dispenser cathode

A cathode that is not coated. A matrix-like structure which, when heated, continuously supplies emission material to the surface.

Dispersion

A term used to describe changes in phase velocity of an RF wave with respect to frequency.

Drift tube

A section of metal tubing, held at a fixed potential that forms a drift space where the electron beam is unaffected by external forces.

Drive

A term to indicate the RF input or RF signal to an electronic device.

Dual-mode

Any device having more than one set of operating parameters, i.e., a TWT operating in both a low-power CW mode and a high-power pulse mode.

Dynamic range for linear operation

The ratio of maximum input power producing 1 dB or less of gain compression to the reference noise level of the TWT.

Earth station

A surface-mounted transmitter or receiver designed to communicate to or via a satellite. Mobile earth stations can be vehicle mounted — land or sea.

ECCM (Electronic counter-counter-measures)

That sector of electronic warfare dealing with the neutralization of an unfriendly *jamming* device.

ECM (Electronic counter-measures)

That sector of electronic warfare dealing with the neutralization of an unfriendly *detection* device.

Efficiency

The ratio of RF power output to dc power input.

Electron

The smallest known negatively charged stable particle. It has a charge of 1.602×10^{-19} coulombs, and all electric charges are presumed to be integral multiples of this number. Electrons constitute the extra-nuclear structure of atoms, and hence are present in all matter. High speed electrons emitted during radioactive decay are called beta rays. Electrons released from a negatively charged electrode by the action of heat, light, ions or intense electrical fields constitute cathode rays.

Equalizers

A passive device providing selective loss over an operating band such that the net gain matches a required profile.

EPC (Electronic power conditioner)

A sophisticated power supply/modulator usually associated with space-qualified TWTAs.

ESM (Electronic support measures)

That division of EW involving actions to search for, intercept, locate and identify radiated electromagnetic energy for the purpose of threat recognition.

Focus electrode

An element which is part of the electron gun that is used to focus the electron beam.

Folded-waveguide circuit

See Coupled-Cavity.

Frequency designations

An "officially" (FCC, DOD, etc.) approved alphabetic designation for a range of frequencies. See Figure 1.

Gain

The ratio of output voltage, current or power to the input voltage, current or power respectively in an amplifier stage, receiver or system. Usually expressed in decibels.

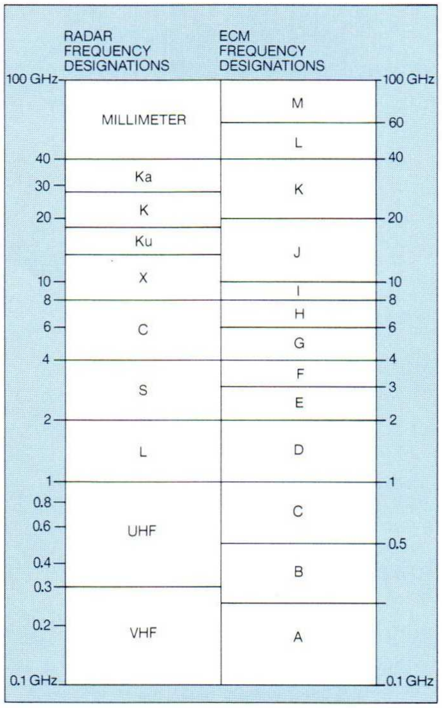

Figure 1 — *Traditional and new frequency designations*

Getter

A device which, when activated, absorbs gasses within an electron tube.

Grid

An electrode mounted between the cathode and the anode of a radio or electronic tube to control the flow of electrons from cathode to anode. The grid electrode may be either a cylindrical shaped ring or wire screen or a spiral of wire through which electrons can readily move.

Group delay

The distortion that results from the phase shift of a transmitted signal through a device is a nonlinear function of frequency. Areas of interest are linear delay, parabolic delay and the ripple component.

Linear delay is the difference in nanoseconds of delay between the ends of the specified bandwidth. Parabolic delay is the center frequency distance in nanoseconds between two defined frequency points within the specified bandwidth, divided by the square of the 1/2 bandwidth in MHz. Ripple is the maximum peak-to-peak variation in nanoseconds of the test data curve about the smoothed curve prepared.

Harmonic drive

The inclusion of phase-conditioned harmonic power in the input RF signal to reduce harmonic capture and improve efficiency at the low end of the operating band of a TWT.

Harmonic interaction

The effect of the harmonic content of the RF input signal on the beam modulation. This is generally undesirable and usually reduces the fundamental power output.

HPA (High Power Amplifier)

Usually refers to a subsystem used in Satellite Ground Terminal applications.

Intercepting grid

A control grid that is not mechanically shielded from the cathode and, thus, intercepts some electrons when a positive potential is applied.

Inter-digital line

A slow-wave structure composed of a comb-like structure with alternate segments being connected together at one end, remaining segments connected together at the opposite end.

Interfering mode

A higher order mode which, when excited, detracts from or distorts the signal in a transmission system.

Intermodulation distortion

1. Impairment of fidelity resulting from the production of frequencies that are the sum of, and the difference between, frequencies contained in the applied waveform. 2. When a signal containing two or more frequencies is applied to the input of a nonlinear device, the output consists of waves having the original frequencies plus additional new frequencies. These new frequencies are the result of intermodulation distortion in the nonlinear device. Undesirable in audio amplifiers and microwave tubes such as klystrons and traveling-wave tubes.

Isolation filters

A passive device or network which isolates a circuit or device from the effects of connected or surrounding circuits or devices.

Jammer

An active Electronic Counter-Measures (ECM) device designed to deny intelligence to unfriendly detectors.

Klystron

A microwave tube which operates on the principle of velocity modulation. Klystrons are designated as reflex klystron oscillator, two-cavity klystron oscillator and multi-cavity klystron amplifier. In each case electrons are bunched in a cavity gap to create oscillations or amplify microwave energy in the case of a multi-cavity klystron amplifier.

Loss buttons

In coupled-cavity TWT's, a patented method for inserting frequency selective loss in order to inhibit the excitation of higher order modes.

Magnetron

A microwave oscillator tube of special design containing a cathode and anode (or resonant cavities) in which a constant magnetic field modifies the space charge distribution and the current voltage relations. Under the action of the RF voltages across the resonators and the axial magnetic field, the electrons from the cathode form a bunched space charge cloud that rotates around the tube axis exciting the cavities and maintaining the RF voltages.

Metal-ceramic

A term applied to the vacuum tight seal, usually a braze joint, between a ceramic structure and a metal structure.

Mode interference

See "interfering mode."

Multi-mode

Having the capability of operating with more than a single set of parameters —see "Dual Mode."

Multi-octave

Capable of operating satisfactorily over a frequency range of 2 or more octaves.

Multipactor

A term to denote an electron-RF field interaction in which the electrons take energy from the RF fields and give up this energy to the surface on which the electrons are collected. Initially electrons are supplied by field emission but the number is increased by secondary emission.

In microwave tubes, multipactor is generally considered to be an undesirable effect and can occur across cavity or drift tube gaps, in output waveguides or involving the ceramic output window. It is detected by observing the output power as it is increased until multipactor occurs, at which point the RF power stays constant. On high power tubes, there will be heating of the surface involved.

Multi-stage collector

A collector with several segments, each segment being "depressed" more than the preceeding segment. This further enhances the collection efficiency thus the overall efficiency of the device.

Noise figure

1. Indicates the ratio of signal-to-noise on the input of a device to signal-to-noise on the output. It is important because it indicates the amount of noise the amplifier contributes to the signal and it is an absolute indicator of the sensitivity of the device. It is usually expressed in dB, and is abbreviated NF. 2. The noise figure of a network is defined as the ratio of the total noise power available at the output port when the input termination is at 290° K to that portion of the total available output noise power engendered by the input termination and delivered to the output via the primary signal channel.

Noise power

1. The noise generated by a device or tube, measurable at the output port, with the input terminated and without a driven signal. Ideally, the output power should be measured using a bandpass filter in order to define the bandwidth properly. Usually symbolized by $N.P_O$ and measured in milliwatts or dBm. 2. A term given to a calculated noise figure and symbolized a NF. This measurement is only an approximate method since it is restricted to several limitations. However, it serves as a useful method in obtaining noise figures when elaborate noise measurement equipment is not available. It is defined as $NF = 114 + NP_O - G - BW$, where NP_O is the measured noise power out of the device, G is the gain in dB and BW is the bandwidth in dB (referred to 1 MHz).

Non-intercepting grid

A control grid that is mechanically shielded from the cathode by a "shadow grid" in such a way that no electrons are intercepted when a positive (with respect to cathode) voltage is applied, to the control grid.

Outgassing

A term used to describe the emission of various gasses from heated metal surfaces during the processing and testing of thermionic devices.

Overdrive

An input signal level greater than that required for saturation, resulting in decreasing output power.

Peak power

1. The power at the maximum of a pulse of power, excluding spikes. 2. The output power, averaged over a carrier cycle, at the maximum amplitude that can occur with any combination of signals to be transmitted.

Perveance

1. A numerical constant representative of the cathode to anode spacing inside a vacuum tube. 2. A quantity which represents saturation current which can flow in a vacuum tube of given geometry. For any shape, the saturation current is proportional to the three-halves power of the applied potential. The perveance is the constant of proportionality. It is symbolized as K and is expressed as

$$K = \frac{I}{E\sqrt{E}} \text{ or } I = K(E)^{3/2}$$

Phase linearity

A term referring to the degree of deviation from a straight line of the phase-versus-frequency characteristic of a device.

Phase tracking

The closeness or similarity of the phase characteristic of a number of devices. This is an important consideration when power combining two or more devices.

Phase velocity

Indicates the transit time of a given signal as it travels along the axis of the RF circuit in relation to the electron beam. It is the product of frequency and wavelength. May not be equal to the free space velocity of radiation.

Power curve

A plot of output power versus frequency.

PPM (Periodic Permanent Magnet)

A term describing a method of focusing a TWT where permanent magnets of opposite polarity are placed side by side along the length of the tube.

Pulse compression

A matched filter technique used to discriminate against signals which do not correspond to the transmitted signal. Used in radar systems for improved detection capability.

Pulse-up ratio

The ratio, usually expressed in dB, between the CW power level and the pulse-power level in a Dual-Mode device.

Radar

Acronym for radio detecting and ranging. A system where a relatively high-frequency radio pulse is used to bounce a signal off a distant object. The direction and time of response give the location of the object.

Redundancy, automatic

In a communications system, a feature which automatically switches to a standby unit in the event of a failure.

Resonant cavity

A short piece of waveguide of adjustable length, and terminated at either or both ends with a metal piston, an iris diaphram, or some other wave-reflecting device. It can be used as a filter, a coupler between guides of different diameters and as an impedance network corresponding to those used in radio circuits, or microwave tubes such as klystrons.

Ring-bar tube

A TWT with a slow-wave structure composed of ring-like segments connected by straps or "bars." This device is capable of higher power levels than a conventional helix tube at a significant reduction in bandwidth.

Saturated power output

A term used to describe that point on the power output versus power input characteristic where an increase in input power does *not* produce an increase in output power.

Screen grid

A grid structure placed between the control grid and anode to shield the control grid from electrostatic lines from the anode. In a multi-mode electron gun the element used to control beam current from the edge of the cathode.

Serrodyne

A term describing the linear translation of the phase of a signal on the helix of a TWT by a linear sawtooth waveform being applied to the helix. It is important because it indicates a property of a helix that enables it to operate as a single sideband frequency translator.

Shadow grid

A grid structure placed between the cathode and control grid and electrically connected to the cathode. This element shields the control grid from interception.

Single-stage collector

A term referring to a conventional collector—may be simply grounded or depressed (see "depressed collector").

Slow-wave circuit

Any structure which "slows" the effective axial velocity of an RF wave in order to maintain synchronism between that wave and an electron beam.

Slow-wave structure

A microwave propagating structure called a helix in one type of a traveling-wave tube. See Slow Wave Circuit.

Spherical diode

A two element (cathode and anode) structure built in such a manner as to duplicate the spherical geometry of the cathode in a typical electron gun. Used for evaluation and analysis of electron and analysis of electron gun designs and for realistic cathode life testing.

Tapered termination

A gradual increase in the amount of loss applied to a slow-wave structure to control reflections within a TWT.

Tapered velocity

A change in the pitch of a helix or height of a cavity to effectively change the velocity of the RF wave. This is done to maintain synchronism between the RF wave and the electron beam.

Tetrode

A Thermionic device having four elements usually a cathode, control grid, screen grid, and anode. In multi-mode TWT's, a term describing the electron gun (cathode, shadow grid, control grid and screen grid).

Time-in circuitry

A combination of circuit elements designed to actuate after the lapse of a certain period of time. Commonly used to apply high voltage to a tube following an appropriate warm-up time after application of heater voltage.

Transfer curve

1. The family of curves for various values of plate voltage in which plate current is plotted as a function of control grid voltage. 2. Specifically with regard to microwave tubes, a curve or family of curves in which input drive power is plotted as a function of output power in an amplifier or system at a fixed beam voltage. Sometimes referred to as a gain-curve.

Triode

A three element thermionic device composed of a cathode, a control grid and an anode.

TR limiter

A Transmit/Receive switching device which limits the amount of power transmitted. Usually employed as a Receiver protect device in a Radar system.

TWT (Traveling-wave tube)

A microwave tube of special design using a broadband circuit in which a beam of electrons interact continuously with a guided electromagnetic field to amplify microwave frequencies.

TWTA (Traveling-wave-tube-amplifier)

A combination of power supply, modulator, and traveling-wave tube usually packaged in a common enclosure.

Uplink/downlink

Uplink refers to the transmission of intelligence to a satellite while downlink refers to the re-transmission to a ground station.

Vacuum envelope

Any structure containing or capable of containing a high vacuum environment. Usually refers to the "body" structure of a thermionic tube.

Velocity resynchronization

Any method for changing the axial velocity of an RF wave to improve the synchronism between that wave and an electron beam.

The Hughes/TWT Connection

The TWT is not a new device. Its remarkable capabilities, and some of its potential applications, have been known for more than thirty years. It was invented during the latter part of World War II by an Austrian refugee, Dr. Rudolf Kompfner, while working on microwave tubes for the British Admiralty.

The TWT was not utilized during that war and remained an experimental laboratory device until the first practical tube was developed by J. R. Pierce and L. M. Field at the Bell Telephone Laboratories (BTL) in 1945. The first details were published in the IRE Transactions for February, 1947.

From 1945 to 1950, most of the development work was done at BTL and Stanford University. By present-day standards, these efforts were relatively low key. BTL, in particular, was interested in the TWT because of its potential application in the communication field.

Meanwhile, the military services had other potential applications in mind — radar and electronic countermeasures. The development of radars during World War II had been rapidly followed by the development of countermeasure techniques to deceive and jam them. The evolution of new radars has, therefore, been partially the result of a continuous need to stay ahead of any new countermeasure tactics which might compromise the radar's effectiveness (and vice versa). The trend in search radar, for example, has been toward much higher powers and toward new techniques which would have the effect of increasing visibility even while being jammed. A good anti-jamming radar must be able to shift frequency over a wide bandwidth quickly to avoid dwelling at the jammer's source frequency.

Similarly, the trend in ECM has been toward wide bandwidth system capabilities where the jammer amplifies wideband noise, or may deceptively retransmit the hostile radar pulse to offset the radar's ability to determine the target's position or track.

Since wide-frequency bandwidths are essential to the employment of all these tactics, an amplifying device capable of broad operating ranges with sufficient gain, output power and efficiency was needed. The TWT was found to be ideally suited for the task, and the military deserves credit for funding many of the early advances in TWT development.

Much of this advance-technology work was done at Hughes. In the late 1950's, with the future of the TWT as a key element in a number of application areas assured, a small group of scientists, engineers and skilled technical support people who had been involved in TWT research throughout Hughes were brought into one organization. The organization later became the Electron Dynamics Division, which now has an established reputation as a leader in the development and production of military and commercial TWTs, TWTAs and related subsystems.

Some of the earliest successes for Hughes TWTs were in the area of space applications. Hughes space TWTs and TWTAs have been used in scientific experiments, manned missions, and communication applications by both military and commercial customers. Early programs included Syncom, the ATS series, the Intelsat series and, more recently, domestic communication satellites both here and abroad. To meet the requirements for future space programs, such as DSCS-III, Intelsat V, Space Shuttle, TDRSS, and the domestic communication satellites, these devices continue to be developed and refined. This work is advancing the state-of-the-art in areas of longer life, lighter weight, higher efficiencies and frequencies, and smaller size.

Hughes TWTs are also meeting the expanding customer requirements in other application areas, such as radar, electronic countermeasures, ground terminals and microwave instrumentation. In all of these fields, on-going programs for further product refinement and basic research continue to produce devices and subsystems of the most advanced designs.

How It Works

The basic form of the TWT has changed very little since its invention by R. Kompfner in 1944, although the performance of these devices today is orders of magnitude better in all attributes.

Amplification in a TWT is attained by causing an electromagnetic RF wave to travel along a propagating structure in close proximity to an electron beam, as indicated in Figure 2.

At the left of this simplified diagram is an electron gun assembly. The gun cathode, when heated, emits a continuous stream of electrons. These electrons are drawn through the anode and are then focused into a tight, narrow tubular beam by a magnetic field and thereby made to travel inside the helix for the length of the tube, and eventually are dissipated in the form of heat in the "collector."

At the same time that the cylindrical electron beam is moving along the length of the tube axis, the desired RF signal is fed onto a "slow-wave" structure consisting, in this case, of a tightly wound wire called a helix. The RF energy travels along the helix wire at the velocity of light. However, because of the helical path, the energy progresses along the axial length of the tube at a considerably lower axial velocity, determined primarily by the pitch and diameter of the helix.

The phase velocity of the RF wave, or the speed at which the energy is moving along the length of the tube, is made slightly slower than the velocity of the electron beam. The near-synchronism results in a continuous interaction between the electron beam and the RF signal. Some of the electrons in the beam are slowed by the RF field, while others are accelerated.

As the "velocity-modulated" electrons move down through the helix they form bunches. These bunches, in turn, overtake and interact with the slower helix RF wave, surrendering dc energy to it. The result is an exponential amplification of the RF signal by the time it reaches the output coupler. Single TWTs have been built with power gains of more than 10,000,000 (70 dB).

Controlling the beam

The electron gun functions like the lens in a projector. The objective is to get as much electron current flowing within as concentrated a beam as possible without distortion. Good gun design is extremely important since it is the source of electrons for the beam. A wide variety of gun designs have been developed by Hughes in an effort to provide better electron beams that can be readily adapted to new TWT types.

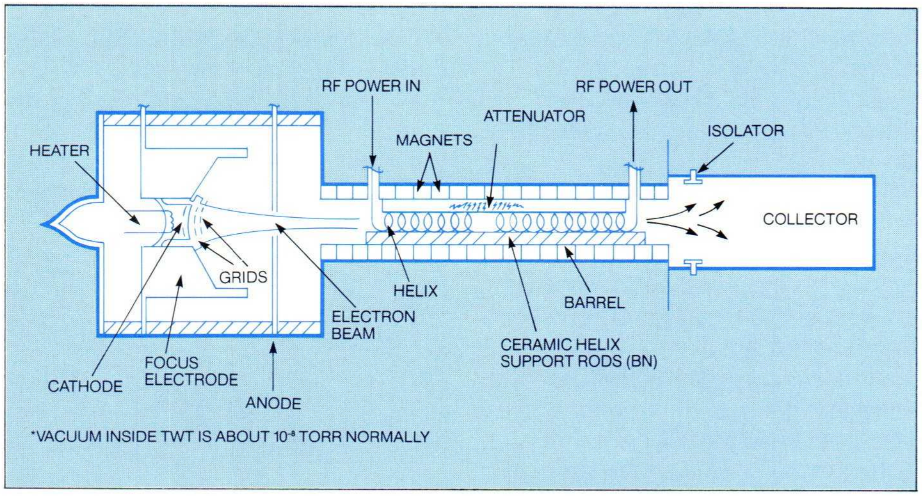

Figure 2 — *Simplified TWT schematic.*

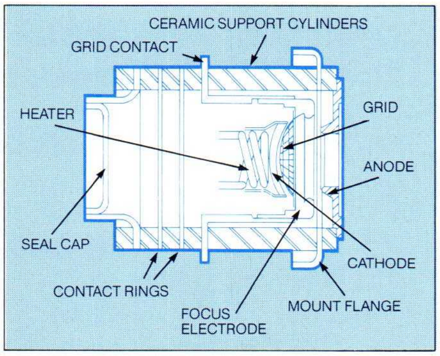

Figure 3 — *A typical grid-controlled electron gun includes a support structure, heater, cathode grid, focus electrode and anode.*

Most TWT guns also include control grids to make it possible to turn the electron beam on and off rapidly with a much smaller voltage swing than is required when the cathode voltage is modulated.

The typical grid-controlled gun has six main elements — the gun shell or support structure, which is usually ceramic; the heater; the cathode or electron emitter; a control grid; a focus electrode to aid in proper formation of the electron beam; and an anode which effectively provides the accelerating field for the electrons. Figure 3 shows a typical gun in cross-section.

Life and reliability of the end product are largely dependent upon the design and type of cathode material used. Many different types of cathode materials have been used as electron emitters, but two have generally become standard. The first is an oxide type with a nickel base and a barium/strontium coating. The second is a dispenser type which typically has an emitting surface consisting of porous tungsten through which barium is dispensed from a base material impregnated with a mixture of barium-calcium aluminates. A variation of this type of cathode, known as M-type cathode, is coated with a porous layer of osmium to lower the work function and allow a lower operating temperature.

A second type of dispenser cathode is the coated particle cathode (CPC) which, as the name suggests, is a structure made up of specially coated particles bonded to a nickel support.

The choice of a specific cathode material is dependent upon the required beam power (current density) and is a function of individual tube design.

Variations on the helix

Although there are many types of helix structures, most are based upon Kompfner's original helix design — still the widest bandwidth structure available.

Figure 4 illustrates the principal component parts of a typical metal-ceramic helix TWT. In the illustration, the metal-ceramic envelope and PPM focusing structure can be seen in the central portion of the photograph. The final assembly, incorporating the balance of the package parts, can be seen in Figure 5.

Figure 6 demonstrates the kind of performance characteristics that can be achieved with this type of slow-wave circuit. The extremely broadband performance is ensured by the highly accurate tolerances held during the helix-winding process. This accuracy is essential to the process of interaction between the electron beam and the superimposed RF wave.

For example, in a 1,500 volt electron beam, the electrons travel at 1/13th the speed of light. Since the RF signal is carried by the helix at about the speed of light, the resulting linear ratio of the helix to the beam must approximate 13:1.

In its basic form, the helix is generally restricted to devices having power outputs of less than 3,000 watts. A number of configurations derived from the basic helix structure have been explored at Hughes, therefore, in an attempt to extend its properties to provide even higher output powers. Early among these was a scheme of using two helices wound in opposite directions. This device, known as a contra-wound helix, extends the useful range of operating voltages up to the 20 to 70 kV range and allows larger transverse dimensions at a given frequency range.

The reason the peak-power capability of helix tubes is usually restricted to about 3 kW output power is that their circuit characteristics are susceptible to "backward-wave" oscillations when the operating voltage exceeds 10 kV.

One solution to this problem is the ring-bar tube, which has distinctly different circuit properties and is not subject to backward-wave oscillations. Ring-bar TWTs are generally designed for voltages in the 12 kV to 30 kV range, with peak-power levels in order of 10 kW to 20 kW. With sufficiently high voltages, peak-power output levels can be in excess of 100 kW.

Another significant TWT development in recent years has been the utilization of basic waveguide mode resonators, coupled together by means of capacitive or inductive apertures to provide either a fundamental forward- or backward-wave circuit. The circuit, developed by Hughes, is known as the coupled-cavity circuit. It is also described as a folded-waveguide circuit since its structure resembles a waveguide folded up in accordian-like fashion.

The coupled-cavity structure effectively slows the RF energy to allow its synchronization with the electron beam — just as in the case of the helix.

The original coupled-cavity structures provided frequency bandwidths on the order of 10 to 15%. Recently, however, methods have been developed for increasing the bandwidth to 40% and more. Tubes utilizing this circuit have been built to produce several hundred kilowatts of peak power at S- through Ku-bands with up to 60 dB gain.

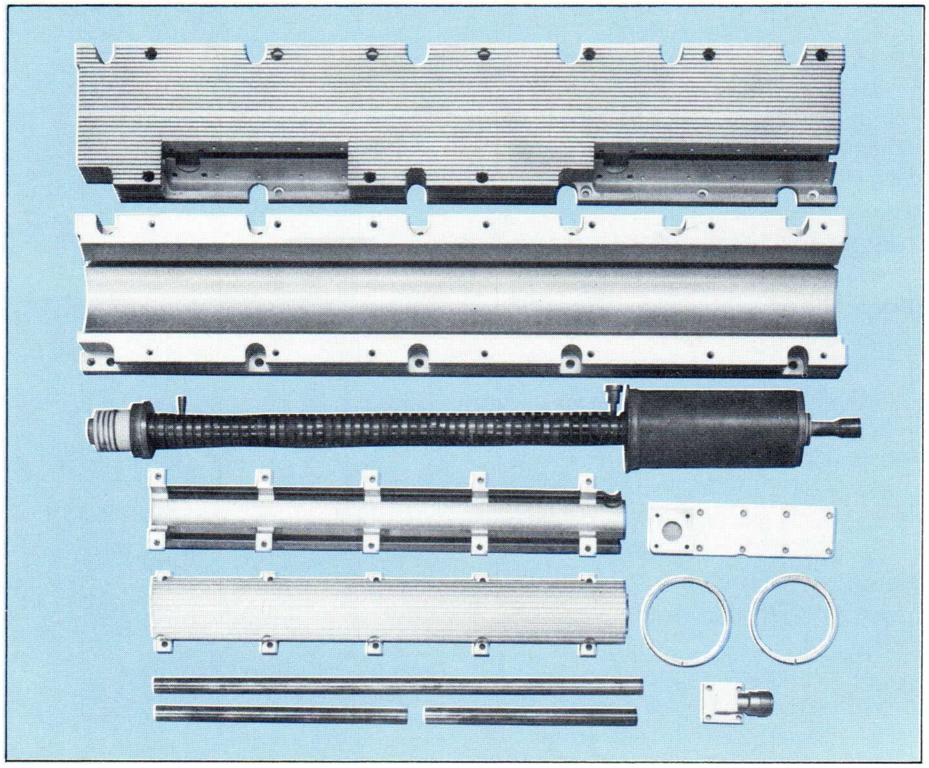

Figure 4 — *658H Traveling-wave tube with major package parts.*

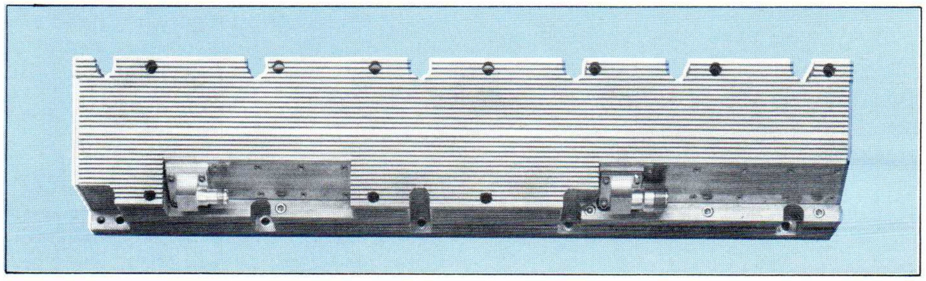

Figure 5 — *Assembled helix TWT*

The inter-digital line is also a version of the coupled-cavity circuit and has found extensive use in low and medium power amplifiers ranging up to one kW peak-power output with gains of about 30 dB.

All of these variations on the helix TWT are described in detail in Section 5.

Comparison with the klystron

At the input of the TWT circuit, the RF signal level is quite low and the resulting modulation of the electron beam is similar to that of the input cavity of a klystron. In the case of the TWT, however, the circuit is nonresonant and the wave actually propagates with the same speed as the electrons in the beam.

The initial effect on the beam is that a small amount of velocity modulation later translates to current modulation, which then induces an RF current in the circuit causing amplification — assuming the proper phase relationships are maintained.

The major difference between this mechanism and that of a klystron is that the TWT interaction is continuous over the entire length of the circuit rather than occurring at the gaps of a few resonant cavities. This continuous interaction is the result of a propagating wave, whereas in the klystron the wave does not propagate. In fact, in the klystron there is generally no coupling between any of the cavities except that afforded by the modulation of the electron stream.

The question can be asked, however, whether any real difference exists between a very narrowband TWT and a broadband klystron — both of which can indeed possess the same bandwidth performance. The answer is that in a true klystron, the wave does *not* propagate. Each cavity operates independently and in complete isolation from all other cavities. There are exceptions to this rule in the form of hybrid configurations in which the pure klystron concept is significantly modified. But these cases do not alter the basic distinctions between the two devices.

Obviously, then, the single most powerful attribute of the TWT is bandwidth. Although there are applications for TWTs where the bandwidth requirement is very small, by and large the primary impetus for their continued development has been applications where the bandwidth is 10 percent or more of the center frequency.

Another advantage intrinsic in the TWT amplification process is that extremely large gains in the neighborhood of 60 dB can be realized with little sacrifice in bandwidth or any of the other desirable properties of the TWT design.

Because the gain-bandwidth product is not the result of an unpleasant tradeoff, as is often the case in other microwave amplifiers, there is no reason to be limited by any such figure of merit. Instead, the gain of a TWT is an exponential function of the interaction length. Each incremental increase in length produces the same incremental increase in gain. This means that measured in decibels, the gain is directly proportional to length, which gives the TWT a distinct advantage over crossed-field amplifiers, for which the gain dependence on length is much less favorable.

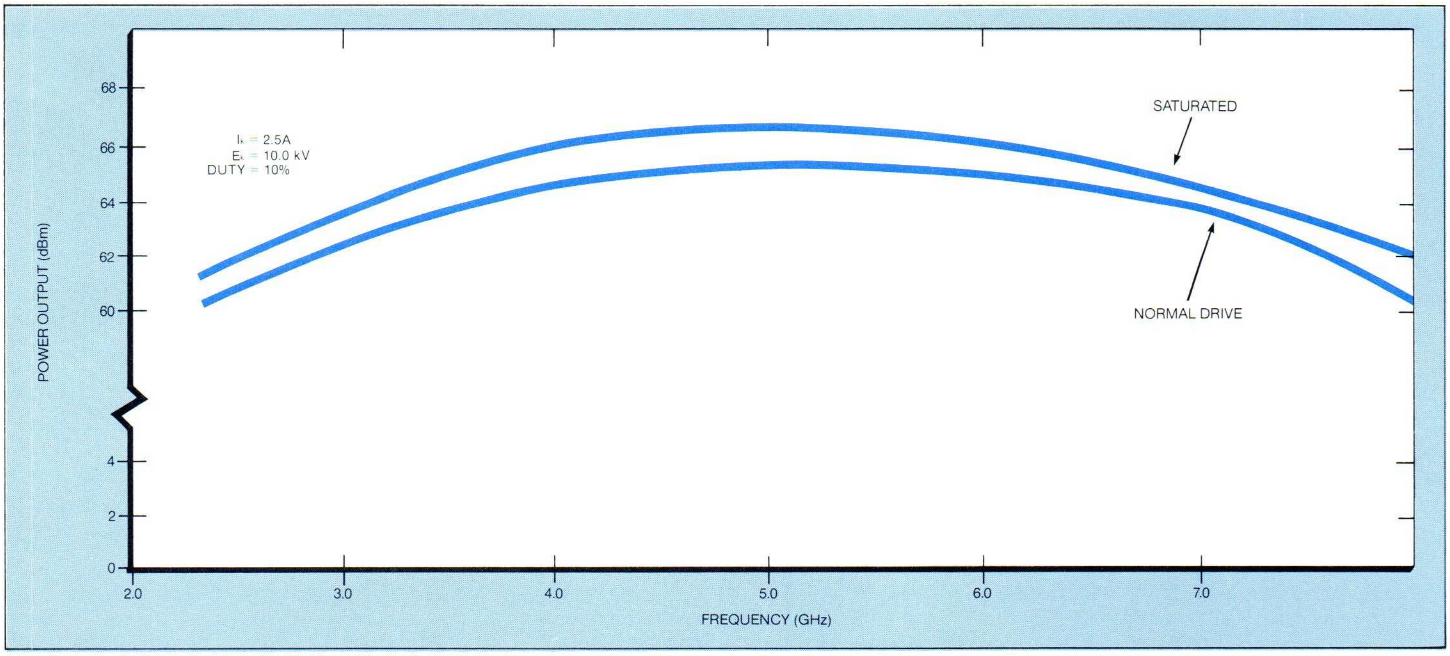

Figure 6 — *Output Power, 658H*

A Choice of Types

Historically, the first circuit to be investigated by R. Kompfner in 1944 was the simple helix, which proved to be the mainstay of the TWT industry 25 years later.

Obviously this circuit must possess some outstanding advantages to have persisted so long in such a commanding position. Probably its simplicity appealed to Kompfner and led him to utilize it in his broadband modulation experiments, since at that time the available techniques for fabrication and assembly of vacuum components were crude and primitive compared to those of the present art.

The early investigators of this elegant circuit probably did not fully realize that almost all of the theoretical measurement standards would show that the helix was far superior to hundreds of other propagating structures which were to be investigated during the formative years of TWT development. In retrospect it is easy to appreciate the basic physical reasons which have given the helix its unchallenged position of leadership, but in the beginning, many hoped that the very first circuit candidate could be superseded by something much better.

Simple first-order considerations of the interaction process between an electron stream and a propagating electromagnetic wave suggest that the following properties determine a figure of merit for the particular circuit being evaluated:

- Minimum stored energy in the propagating wave
- Maximum axial electric field in the region of the electron beam
- Constant phase velocity (no dispersion)
- No interfering modes

The last property is one which must be qualified since it is highly dependent upon the specific design under consideration, but in general the helix possesses a very manageable mode structure that is indeed superior to almost all other substitutes.

The dispersion characteristic of the helix is probably the single most significant property that has caused this circuit to find such acceptance for broadband application. ECM systems and broadband test equipment demand an octave or more of good performance from a TWT to provide maximum coverage in a single amplifier.

Widest bandwidth

No circuit has ever rivaled the helix in bandwidth capability, and most do not come close in this department. It behaves very much like a single wire above a ground plane, propagating a TEM mode. Such a circuit is, of course, completely nondispersive. Since the helix is much more complicated than a single wire over a ground plane, it does not provide infinite bandwidth and does exhibit mode interference—at a very well-defined point where the circumference is exactly one-half the wavelength of the propagating frequency.

Since the helix geometry does not involve large opposed metallic surfaces, the stored energy for a given power level is naturally quite low. Almost any conceivable alternative to the helix employs more massive metal surfaces, which provide an equivalent capacitance for the storage of energy and a lowering of this figure of merit.

The helix also provides a very convenient electric-field configuration. Inside the structure the field is somewhat constant (it does vary) over the cross section of the pencil beam which is generally utilized as the energy source. It is difficult to imagine another geometry with the same natural uniformity in this regard. Most alternative circuits do not provide, therefore, as strong an interaction between the electric field and the beam.

Analytically, this parameter is referred to as the circuit impedance even though it relates to the electric field which is available for interaction with the electron beam and is, therefore, not the same impedance as is generally employed in ordinary microwave circuit investigations.

Mechanical advantages

Aside from purely electrical considerations, the helix is almost ideal from a mechanical viewpoint. It lends itself to simple fabrication techniques which are highly precise. And it can be accurately assembled in structures which fit well with the rest of the TWT package. Circuit symmetry is essential if an elegant design is desired at a reasonably low cost.

The first helix TWTs constructed in the late 1940's were characterized by their fragility and very low thermal capacity. As a consequence, their early development was directed primarily towards low-power applications where the signal power was a few watts or less. These devices were tempermental and short-lived because of the poor techniques of design and construction.

Today, by contrast, helix-type TWTs are quite capable of delivering several kilowatts of CW power at S-band and C-band over an octave of frequency coverage. The lifetime and reliability of many examples exceed most other types of active microwave sources. In short, this generic device has advanced in capability by orders of magnitude as a result of 25 years of sustained high-level development efforts by the major TWT manufacturers.

Helix-derived TWTs

To create suitable high-power beams for the generation of more than 5 kW of peak RF power, it is almost mandatory to utilize beam voltages in excess of 10 kV—assuming a conventional TWT design approach is to be employed.

Above 10-kV beam velocities, however, the pure helix is a poor circuit for traveling-wave interaction because of its electric-field characteristics. Historically, therefore, investigators have proceeded in two separate directions, both of which have proved successful in their efforts to develop suitable TWT circuits for use above 10 kV.

The first attempts concentrated on a modification of the simple helix circuit by employing another helix coincident with the first, but wound with a reversed pitch. This came to be known as the contra-wound helix, and later versions were designated as the ring-bar circuit. Figure 7 illustrates these geometries.

It can be shown from simple circuit considerations that the phase velocity of these two configurations is going to be much higher than a simple helix, and consequently synchronous beam voltages far in excess of 10 kV should be realizable.

This is, in fact, the case. And many successful TWTs have been developed using this structure in the peak-power range of 5-200 kW at frequencies through Ku-band and higher.

The basic assembly is almost identical to that of a conventional helix tube in that the RF structure is supported on ceramic rods inside a long tubular barrel. Unfortunately, the thermal capacity of such a circuit is not much different from that of the simple helix, so the ultimate average power capability is restricted to roughly the same numbers for a given frequency and a given size.

Ring-bar TWTs

Ring-bar TWTs can conceptually be considered as structures derived from multiple helix circuits — in particular, the twin crosswound helix.

The ring-bar circuit has, however, significantly higher interaction impedance than a helix, and is thus capable of more efficient beam power conversion and larger gain per wavelength.

Such tubes also exhibit superior RF-stability with respect to backward-wave oscillations (BWO), compared to helix tubes, and are therefore capable of operating at higher voltages, as well as of producing higher peak-power levels. They are also capable of handling larger average RF power loads, and thus they frequently use nonintercepting gridded guns rather than intercepting (single) gridded guns characteristic of high-power helix tubes.

Unlike most helix tubes, the bandwidth of a ring-bar tube is generally limited to about 10% to 20%. As a result, the ring-bar design finds its most frequent application in radar systems. Typical is the Hughes 8729H prototype ring-bar TWT, with performance characteristics summarized in Figures 8 and 9.

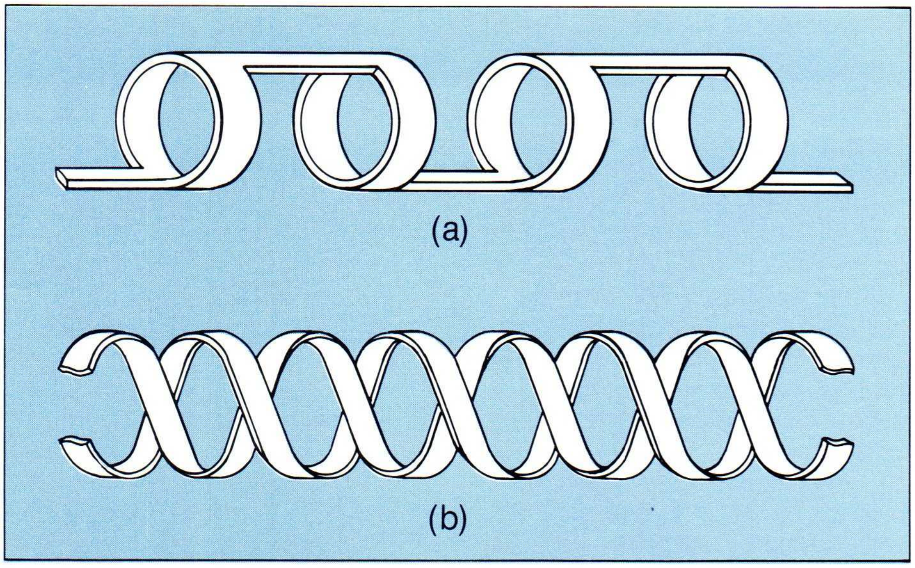

Figure 7 — *(a) Ring-and-bar type contra-wound helix. (b) Two-tape contra-wound helix.*

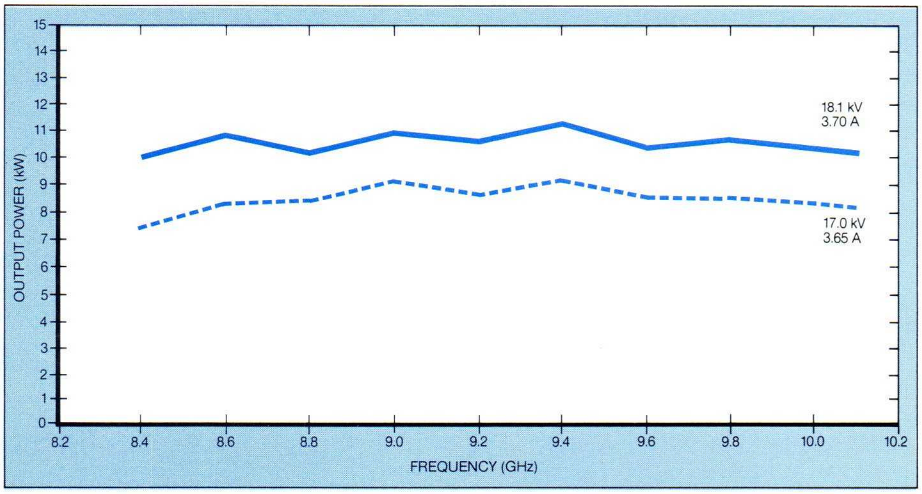

Figure 8 — *Peak output power of ring-bar tube 8729H.*

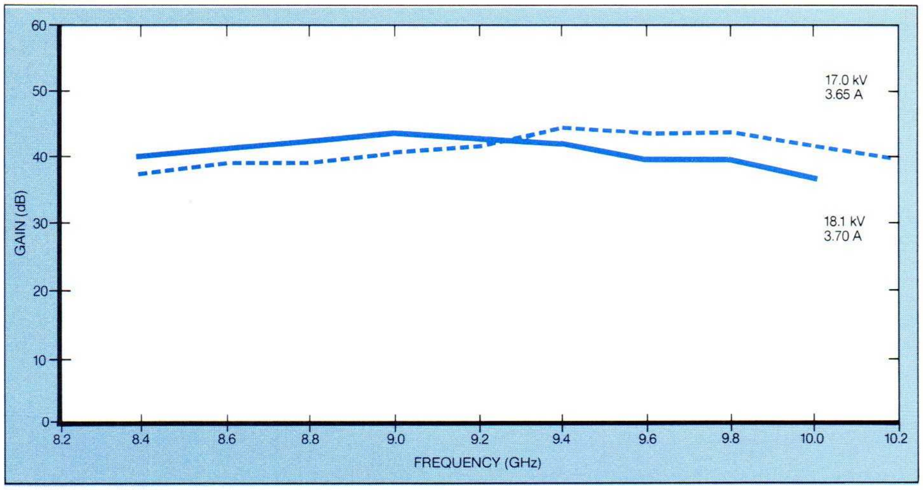

Figure 9 — *Saturated gain for ring-bar tube 8729H.*

Coupled-cavity TWTs

The second basic approach to high-power circuits—other than variations on the helix—has been far more popular because of its many distinct advantages and tremendous flexibility. It represents a complete departure from the helix concept both in its electrical behavior and mechanical configurations.

The best generic description is a high-power filter circuit with bandpass characteristics, a form of traveling-wave circuitry which was first considered at the very beginnings of the technology in the 1940's.

Any repetitive series of lumped LC elements constitutes a propagating filter-type circuit, and the techniques for synthesizing these circuits are well established in the art. Almost any phase characteristic desired can be realized if the proper LC elements are selected. The real test comes when one tries to transform these choices into a practical mechanical structure that can be fabricated and assembled in accordance with accepted vacuum-tube techniques.

The early attempts at this task resulted in some very interesting museum pieces, which probably consumed thousands of man-hours of fruitless labor. These were rejected because they lacked simplicity and symmetry, which would have made them practical from the viewpoint of cost and flexibility. Probably as a result of these frustrating endeavors, the real objectives were properly identified and the main thrust proceeded in a direction which satisfied the basic requirements of a good universal filter-type circuit.

All of this early work culminated in the discovery and development of the coupled-cavity circuit, which now constitutes the fundamental building block of an extremely important class of high-power TWTs. Its remarkable acceptance is clear testimony to its inherent superior qualities, which can be summarized as follows:

- Excellent electrical characteristics in terms of impedance, bandwidth, and mode structure
- Mechanical simplicity, circular symmetry for easy machining and assembly
- Form factor ideally suited to PPM focusing
- Rugged from both a mechanical and thermal viewpoint
- Very versatile; simple procedures for scaling frequency, power, and bandwidth

The versatility of the coupled-cavity circuit is demonstrated by the fact that it is widely used from L-band to millimeter waves and for power levels from 1 to 500 kW. Probably 90% of all high-power TWTs employ this basic type of filter structure.

Coupling through the slots

The term "coupled cavity" stems from the striking similarity of the individual unit cells to an ordinary klystron resonant cavity. In the latter case, of course, there is no coupling, so each cavity is completely closed. In the case of the TWT circuit, coupling is provided by a long slot in the wall of each cavity, as illustrated in Figure 10.

This slot strongly couples the magnetic component of the field in adjacent cavities in such a manner that the passband of the circuit is primarily a function of this one variable. For very small slots, or coupling holes, the passband is quite narrow. When the slot angle (Ø) is somewhat larger than 180° the passband is close to its practical limits.

The drift tube is formed by the re-entrant part of the cavity, just as is the case with a klystron. Its length is determined by beam-interaction considerations, but the optimum design for a given bandwidth is not a critical function of the gap length. In fact, all of the important cavity dimensions can be adjusted over a rather broad range to accommodate tradeoffs between thermal requirements and electrical performance without seriously degrading circuit capability.

Once the design is made, however, the tolerances of the circuit dimensions must be very closely maintained. Each half-cavity section can be fabricated in laminated form, which is ideal for the assembly and brazing operations. The individual parts are almost self-jigging, which assures very accurate alignment and spacing between cavities.

Liquid cooling of the circuit can be provided by properly channeling the outer diameter such that the coolant flows around the massive copper walls of the individual sections. In extreme cases, the coolant can be channeled around the drift tubes to absorb beam interception heating directly, at the price of greater fabrication complexity.

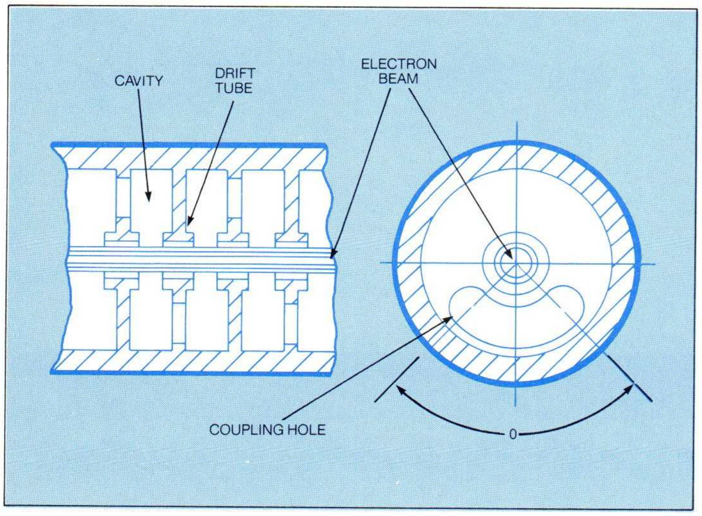

Figure 10 — *Basic coupled-cavity circuit.*

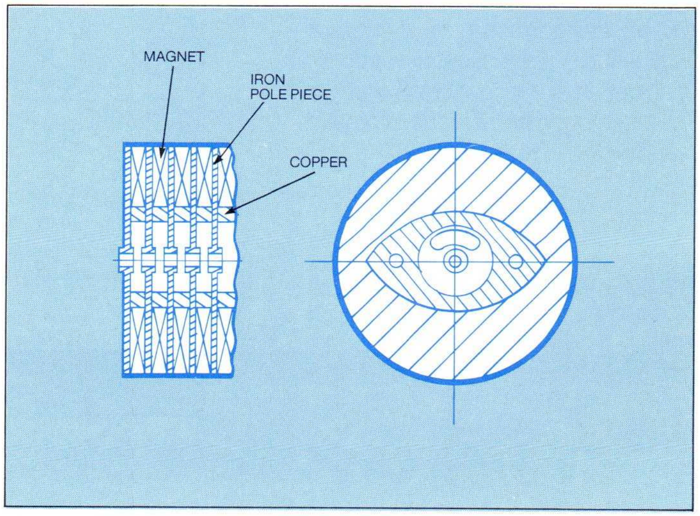

Figure 11 — *Coupled-cavity circuit with integral periodic-permanent-magnet (PPM) focusing.*

Lightweight focusing

Perhaps the most outstanding advantage of the coupled-cavity circuit from the user's viewpoint is its natural adaptability to lightweight PPM focusing. In many airborne systems, the weight and bulk of a separate focusing solenoid, along with its sizable power supply, are unacceptable. In these situations a TWT would be rejected if it were not possible to simplify the focusing requirements with a PPM structure.

Figure 11 illustrates the manner in which the PPM focusing system and the RF circuit are combined together to bring the magnetic field down to the beam periphery. The individual cavity walls are fabricated from high purity iron, subsequently plated with copper to reduce RF losses. The iron channels the magnetic field in a very efficient way to the beam region where its effectiveness is maximized.

If such a geometry were not available for this purpose, it is highly unlikely that the typical high-powered TWT could even be focused with available permanent magnet materials. Generally these beams are very dense and require powerful magnetic forces to hold them together.

On the outside of the vacuum envelope the iron pieces (extensions of the cavity walls) are made large enough to contain most of the magnetic material utilized in the focusing cells. Such a configuration improves the accuracy of alignment of the magnetic field and also gives good mechanical support to the entire assembly.

From Figure 11 it is apparent that some degree of circular symmetry is lost in the PPM geometry due to the presence of the cooling channels. With the iron pole pieces, it is generally desirable to provide liquid-cooling lines close to the cavity walls to minimize the temperature drop from the internal sections of the tube to the outside environment.

It should be emphasized that iron is not a good thermal conductor when compared to copper, and, furthermore, the presence of the permanent magnets creates some difficulty in accommodating simple cooling schemes. For low-to-moderate average-power applications these considerations are not important, and less complex geometries are then possible.

Millimeter-wave tubes

The work which has been done in the development of high-power millimeter-wave tubes has been largely influenced by the needs of actual systems operating in this frequency band. Significant results of the work done in this band are summarized by Figures 12 and 13, which define both the CW and the pulsed-power levels that have been achieved.

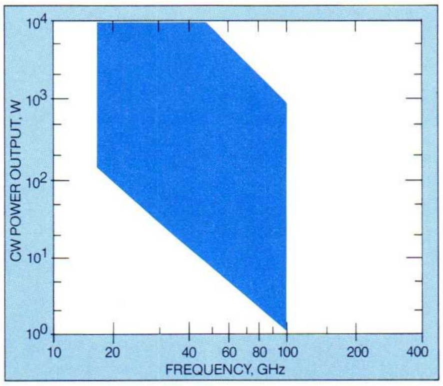

Figure 12 — *The status of CW millimeter-wave tubes.*

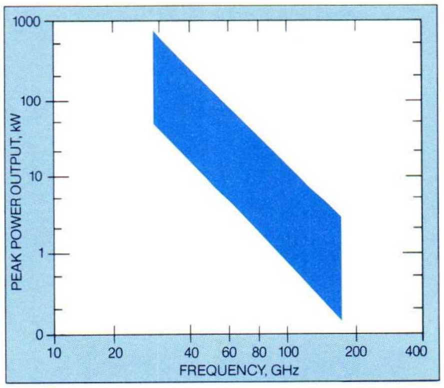

Figure 13 — *The status of pulsed millimeter-wave tubes.*

The lower edge of the shaded portions of these diagrams indicate the state of the art as it existed in 1960, and the upper edge indicates the current state-of-the-art. However, these curves are not meant to imply that the technology does not exist today to construct tubes which fall outside the shaded regions, but only that there have been no pressing system applications that have demanded it.

In general, millimeter-wave tubes utilize very low perveance electron guns, which create some unusual electron-beam focusing problems assocated with the proper containment of the "thermal" electrons. Hence millimeter-wave tubes have frequently been equipped with heavy solenoids. Recently, however, PPM focusing of an electron beam suitable for a millimeter-wave tube has been demonstrated.

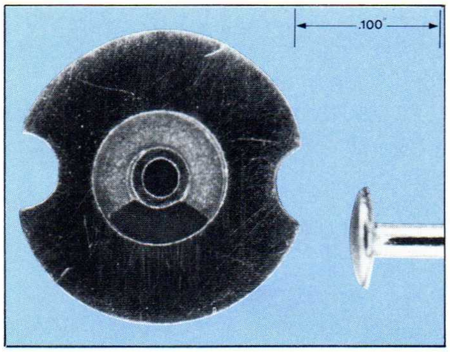

Figure 14 — *Photograph of copper circuit part for a millimeter-wave tube.*

This development was in response to a specific application which called for a lightweight tube and was made possible by the recent development of new magnetic materials capable of extremely high energy products. Aside from the focusing structure, the major challenge in the manufacture of millimeter-wave tubes is the precision and tight tolerances required for the extremely small circuit parts. To illustrate this problem, Figure 14 is a photograph of an OFHC copper circuit part in relationship to the head of a regular sewing needle. From this picture, one can appreciate the small size and the assembly difficulties involved in the fabrication of circuits utilizing these parts.

TWT Design—Inside and Out

The purpose of this section is to give the reader a general insight into the design of TWT devices, their limitations and potential capabilities. Toward the end of the section, consideration is given to power supplies and other "accessories" required to integrate the TWT into a working system.

Electron gun

With increasing performance demands on TWTs, the quality of the electron gun design is a key factor at Hughes. There is, therefore, a specialized group within Hughes which concentrates in gun design, focusing, and related electron-optical problems.

Design tools, such as computer programs for analysis and gun analyzers for experimental evaluation, are continuously upgraded and improved. A file on previously designed guns of all types is maintained for reference and as a basis for new designs.

Electron guns used in traveling-wave tubes are generally convergent. This means that the current density at the cathode, i.e., the cathode loading, is significantly lower than the current density in the beam and below a specified maximum value. Cathode loading is related to the cathode life; reduced cathode loading will allow the cathode to be operated at a lower temperature and will provide a longer cathode life.

The design of high perveance, convergent guns is well established and is based on Pierce's "spherical diode" concept—a conical convergent electron flow with uniform current density in the beam cross-sections. The design procedures provide data on cathode and anode curvatures and their aperture angles, and radii for specified gun design requirements, but do not give sufficient details on the shape of the beam-focusing electrode and anode.

The design of these electrodes can be determined with an electrolytic tank in conjunction with Langmuir's theory. Use of the tank enables the designer to evaluate a variety of electrode shapes and to establish an optimized configuration.

Experimental design methods of this type have recently been replaced by theoretical approaches based on analytical extension methods. The theoretical methods have been computerized and provide faster and much more accurate electrode designs—with improved quality of the gun optics.

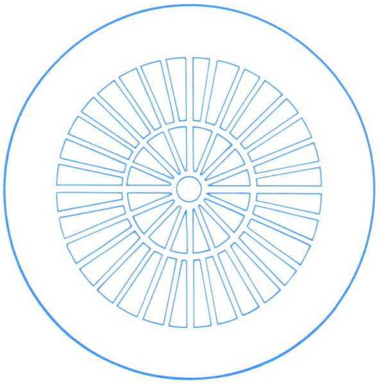

Figure 15 — *Grid with radial vanes.*

Single-gridded guns

It is often required that the current control of guns be accomplished by relatively small voltages. This is possible with a single-grid structure, placed in front of the cathode, provided that the thermal load on the grid due to interception is within acceptable limits.

A commonly used type of grid structure consists of a mesh or, better still, a large number of radial vanes supported by one or two rings. Figure 15 shows a grid structure of this type.

Nonintercepting gridded guns

The insertion of a grid structure into the electron gun will perturb the equipotential distribution in the gun and cause electron-optical lens effects on the electron trajectories passing through the grid.

A portion of the cathode current will also be intercepted by the grid, as determined by the screening factor of the grid. As a result, single-grided guns such as that shown in Figure 16, can only be used for low-average-power tubes because of the thermal power limitations of the intercepting grid.

High-average-power tubes employ, therefore, nonintercepting gridded guns, which use a precisely aligned pair of grids, with the "shadowing" grid closest to the cathode electrically connected to the cathode, as shown schematically in Figure 17.

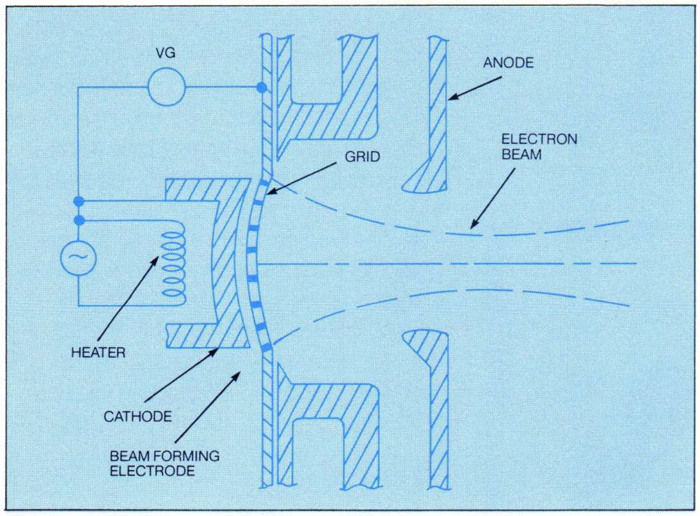

Figure 16 — *Schematic of intercepting gridded gun.*

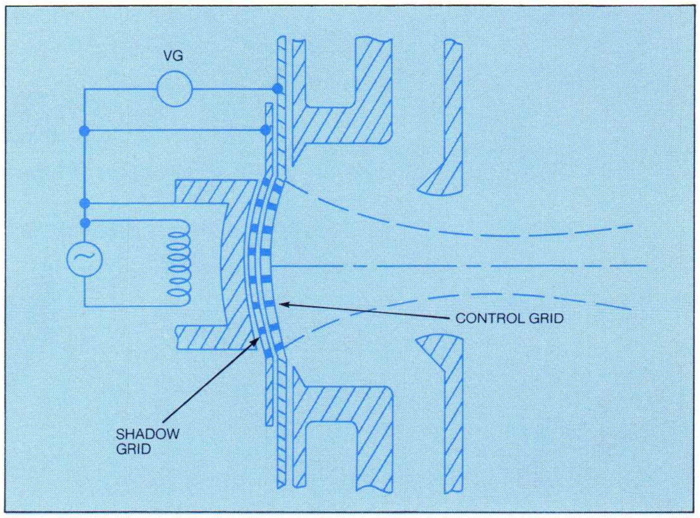

Figure 17 — *Schematic of nonintercepting gridded gun.*

The grid configuration reduces grid interception of the control grid from about 10% to a very small fraction of one percent, thus making it possible to substantially increase the average power capability. Figure 18 shows typical gridded electron gun characteristic curves which determine the specific point of tube operation, as well as the required negative voltage for tube cut-off.

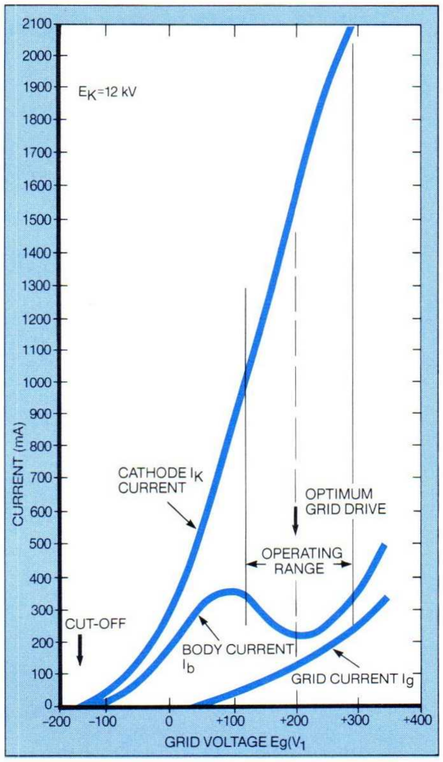

Figure 18 — *Focusing characteristics of gridded gun.*

The focusing structure

All TWTs require some means of holding the cylindrical electron beam in shape as it travels along the inner diameter of the interaction structure. Without a focusing structure, the beam tends to disperse or spread out as a result of the mutual repulsive electrical forces between electrons.

A magnetic field in varied forms is used for this purpose. Such a field of proper magnitude will confine the electron beam to the pencil-like cylindrical shape it must maintain. The four principal types of magnetic focusing discussed here are illustrated in Figure 19.

Of these, the solenoid is still regarded as one of the best magnetic focusing structures. Its magnetic lines are parallel to the direction of travel of the electrons, and it can be accurately aligned with the beam. It provides excellent beam collimation and will continue to be used in applications where the last bit of average power is required from a tube—so long as tube size and weight are not critical factors.

Most of the very-high-power TWTs to date have utilized solenoids. In fact, Hughes has pioneered a technique for wrapping the solenoid directly onto the tube barrel. This optimizes the alignment between the tube axis and the magnetic axis. It also brings the solenoid windings as close to the tube axis as possible, providing the required magnetic field with the very minimum size and weight. A secondary benefit is that less dc power is required to provide the magnetic field.

In certain structures, however, where the interaction structure is short enough, permanent magnet focusing is often utilized in lieu of the bulky solenoid. Because of the length limitations, this type of focusing is generally restricted to low-gain or low-power tubes.

Perhaps the most profound development in beam control has been the evolution of double-period, periodic-permanent-magnet (PPM) focusing—particularly its adaptation to high-power TWTs. Previous to Hughes' patented developments in this field, the fundamental limitations of the PPM design were thought to be

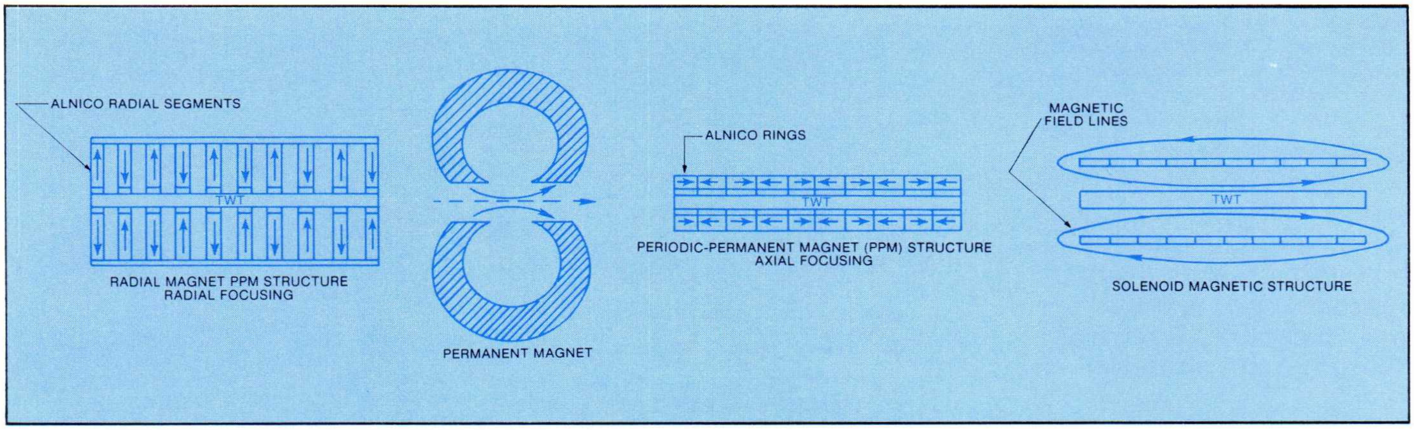

Figure 19 — *Among the four principal methods of magnetic focusing, the solenoid is considered the best choice.*

so restrictive that it could only be utilized in low-power TWTs where the beam power density is typically quite low. Yet one of the greatest needs for this lightweight focusing method has been at the high-power levels required for many airborne and space applications where tubes with focusing solenoids have been too large and heavy. PPM focusing has now been successfully utilized to achieve 12 kW of average beam power in a 125 kW peak power.

Figure 20 shows a cross-section view of the Hughes 774H, a high-power pulsed helix TWT, complete with the focusing structure and external package. The tube is of metal-ceramic construction having a total weight of only five pounds. The PPM focusing structure is composed of round magnet discs shown in the cross-section.

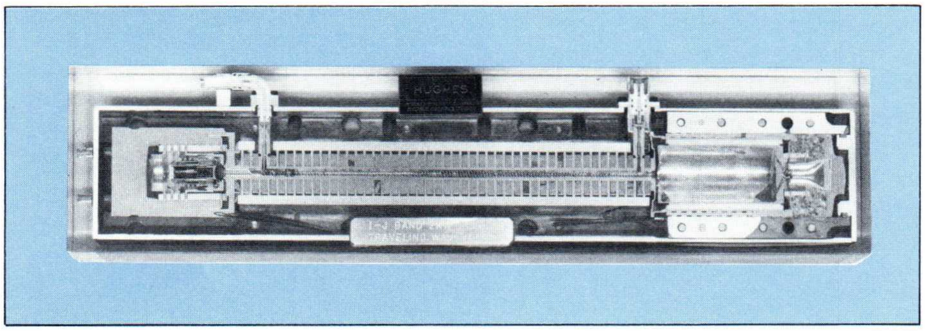

Figure 20 — *The Hughes 774H X-band high-powered helix TWT weighs only five pounds and is rated at 1.25 kW minimum power output with a 0.04 duty cycle.*

Dissipating the beam

The collector dissipates the electrons in the form of heat as they emerge from the slow-wave structure. This is usually accomplished by thermal conduction to a colder outside surface where the heat is absorbed by circulated air or liquid. The specific collector is determined by the method of cooling used and the amount of energy that must be dissipated.

The simplest collector is a single-stage collector with the voltage typically set between 40 and 65 percent of the cathode voltage with the same polarity. In this way the electrons which have been accelerated in the gun, and have had some fraction of that energy removed by the amplification of the circuit wave, are further slowed upon entering the collector—with a resultant recovery of kinetic energy of the beam.

A schematic of a single-stage collector is shown in Figure 21. This type of collector is usually employed when efficiency is not a primary objective or when power supply restrictions only allow a single potential to be available to the collector.

When greater efficiency is required, a doubly depressed collector is used which effectively sorts the electron velocities into two groups. The slower group is collected on the first stage (V_1) as shown in Figure 22. The more energetic group is collected on the second stage (V_2) which is depressed further. The average kinetic energy recovered by a two-stage depressed collector is greater than that of a single-stage collector since more electrons of the spent electron beam are able to be collected on depressed collector electrodes.

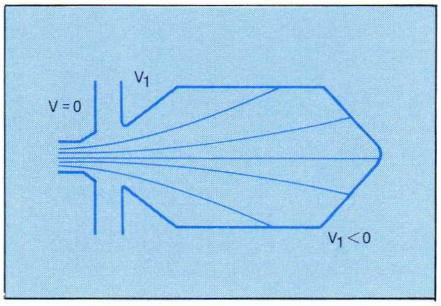

Figure 21 — *Schematic of single-stage collector.*

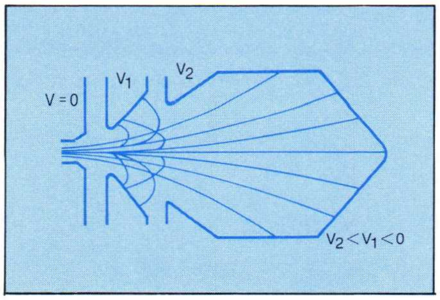

Figure 22 — *Schematic of two-stage collector.*

A three-stage collector provides an even greater degree of electron sorting and is usually employed only when high efficiency is of primary importance. A schematic of a multiple-depressed collector is shown in Figure 23. Here the beam is sorted into three different energy groups, and each stage contributes to the overall recovery of spent beam energy.

It has long been recognized that significant power savings could be obtained in a TWT by decelerating the spent electron beam and collecting it at a reduced potential. Depressed collector operation will, therefore, improve the tube efficiency, as well as reduce the thermal load of the collector and simplify its cooling requirements.

The amount of collector depression is, however, limited by the inherent velocity modulation of the spent beam. A part of the kinetic beam energy, which serves

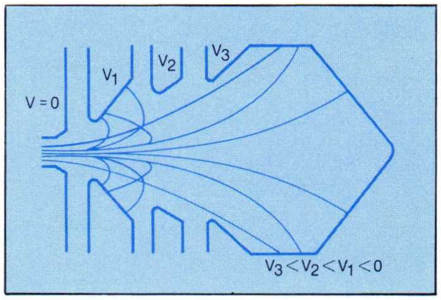

Figure 23 — *Schematic of three-stage collector.*

as the energy source for the traveling-wave tube, is converted into RF power in the interaction region. As a result, the spent electron beam will have a velocity spread, and its average velocity will be reduced.

When the collector potential is depressed to a greater degree than the corresponding velocity of the slowest spent beam electrons, these electrons have insufficient energy to penetrate into the collector. Therefore, their flow will be reversed and backstreaming current is then initiated.

Such backstreaming is undesirable. Not only will it defeat the power-saving purpose of collector depression, but it may also produce an excessive thermal load on the circuit, interfere with the RF performance, and cause instabilities.

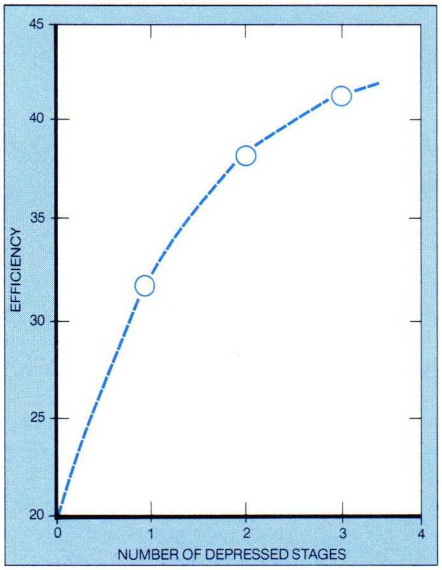

Figure 24 — *Efficiency versus the number of depressed collector stages for S-band traveling-wave tube.*

The incremental efficiency improvement which can be obtained by increasing the number of depressed collector stages diminishes as the number of stages is increased. Efficiency as a function of the number of depressed stages is shown in Figure 24 for a space TWT. For this reason the number of depressed stages is generally limited to three or four.

Multi-stage collectors also offer the advantage of substantial power savings during small signal operation or without RF drive. This, in turn, offers a near constant thermal load, as shown in Figure 25, for a 10-watt device.

The vacuum envelope

One of the major disadvantages of early helix circuit tubes was the fragile glass-vacuum envelope enclosing the tube parts. However, the art of packaging has reached the point where such glass structures are sufficiently well-supported to withstand almost any environment and all but the highest shock or G loads.

A recent innovation, however, in the manufacturing of helix TWTs has been the successful utilization of metal and ceramic materials in place of glass. These tubes can not only withstand higher G loads, but can be vacuum processed at higher temperatures — typically 600° to 700°C as opposed to 450° in the case of glass structures. This ensures considerably more complete "bake-out" of undesirable gasses entrapped in the tube, providing improved reliability at higher tube operating temperatures.

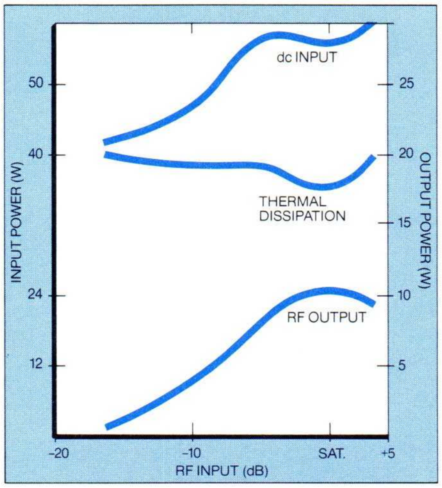

Figure 25 — *Multi-stage collectors offer substantial power savings during small-signal operation or without RF drive resulting in a near constant thermal load.*

In a practical TWT, attenuators (lossy sections) are placed along the helix (slow-wave structure) to provide stability by absorbing internal and external mismatch reflections. The attenuators also isolate external system components on the output arm from those on the input arm. A typical high-grain TWT will provide up to 80 dB or more isolation or "cold" insertion loss. Without this "loss" added to the internal structure, it would be possible for reflected RF power to travel back to the input causing regeneration. In a high-grain device this would, in turn, cause a self-induced oscillation.

Since that portion of the slow-wave structure dedicated to attenuation does not contribute to the gain of the tube, the effect of adding attenuation increases the length of the device. The higher the gain, the more attentuator sections will be required. A rule-of-thumb is about 20 dB per section, so a tube with 50 dB gain would have three active sections and two attentuator sections.

Power supply interface

The TWT and the power supply are the key elements in any power amplifier. Equally important are the interfaces between these elements to insure optimum performance and maximum life of the resultant traveling-wave tube amplifier (TWTA) or high-power amplifier (HPA).

There must be a continuing interaction between the TWT and power supply designers since the design of both elements must go far beyond "voltage and current" requirements. Cooling, protection (TWT and power supply), mechanical and control interfaces require detailed attention.

As a result, today's high performance TWTAs and HPAs are not a power supply designed around a TWT, but rather TWTs and power supplies are designed together (Figure 26) to meet performance and reliability criteria.

The following are some of the interface considerations used in the design and implementation of Hughes HPAs and TWTAs for commercial, military, space, satellite earth stations, radar, ECM, and instrumentation applications.

Power supply regulation need be only as tight as required to meet RF performance characteristics and to prevent defocusing of the TWT electron beam as a function of line, load, and environmental changes. For example, in many cases the TWT collector supply need not be highly regulated to meet these requirements, and can often be left unregulated to vary with line fluctuations. In this case, a highly regulated power supply may be overly complicated and reduce reliability.

Ripple from the power supply and the TWT pushing factors will determine the amount of signal distortion contributed by the TWTA in the areas of amplitude, phase, and frequency modulation. Less sensitive electrodes require less power supply filtering. Conversely, more sensitive electrodes (higher pushing factors) require more power supply filtering to meet sophisticated systems requirements.

ON/OFF control of the TWT is not only important as an operational consideration, but also from a protection viewpoint. Hughes HPA/TWTA circuitry can rapidly detect high helix or body current, arcs, high reflected power and other abnormal conditions. But unless the TWT beam power can be removed equally as fast, the value of this protection feature is compromised. A proven approach for rapid turn-off of the TWT is the use of a modulating anode and associated power supply circuitry.

Time-in circuitry must be designed to provide a reasonable TWT warm-up time from a cold start, and the minimum down time in the event of a momentary power outage. Both direct and proportional type heater timing circuits must assure that the TWT cathode is at the proper operating temperature before application of the beam power. Improper timing can cause TWT out-gassing and failure.

Body/helix current overload protection is a critical consideration in the design of any high-power amplifier. Abnormal TWT defocusing can occur as a result of improper power supply voltages, RF overdrive, output high reflected power, and other conditions. The object of a body/helix protection circuit is to limit the amount of time that defocused electrons can intercept the slow-wave structure to prevent TWT failures. This protection circuitry must be fast-acting and tolerant of normal intercept currents due to TWT aging and turn-on/turn-off characteristics.

Other interfaces such as mounting, cooling, thermal protection, and fail-safe power supply circuitry must be considered to prevent damage to the power supply and TWT in the event of a failure of one of these elements. RF input and output interfaces must not place unnecessary stress on the TWT RF connection and vacuum windows. In summary, both the TWT and power supply should be

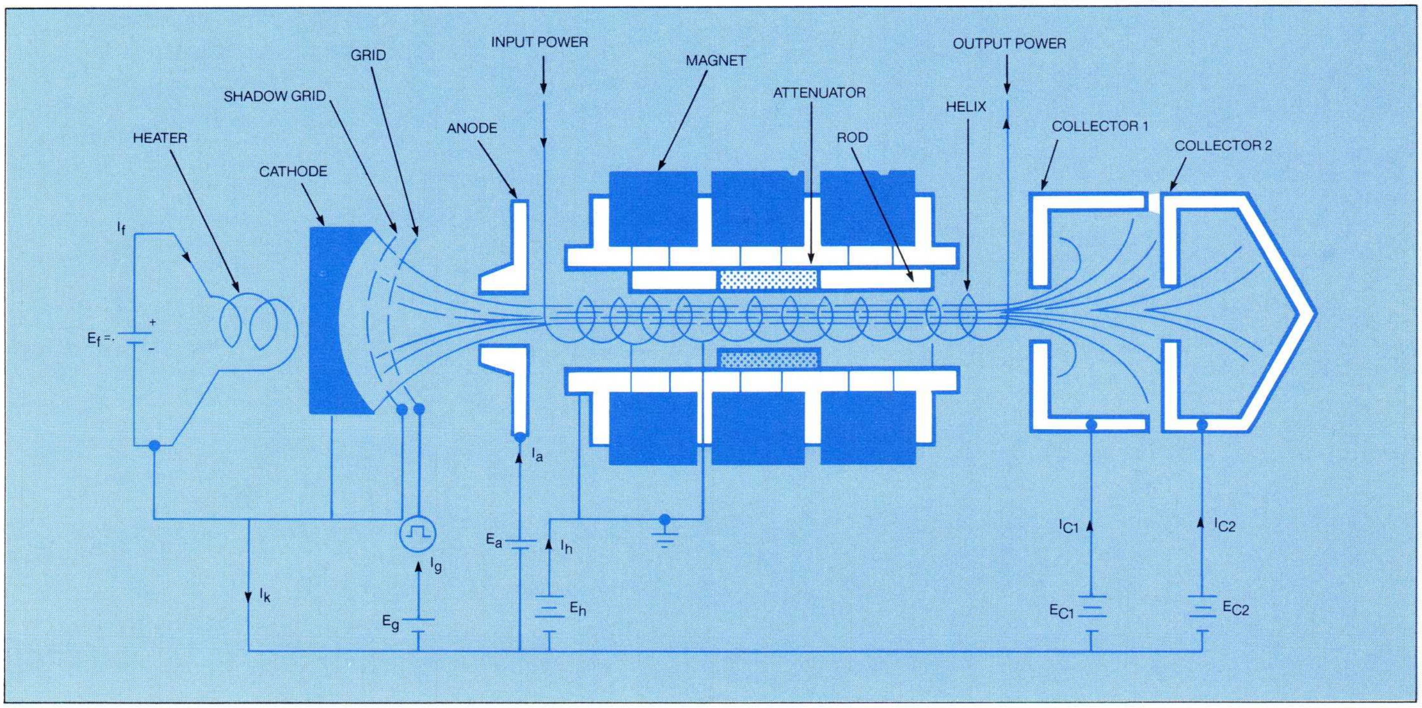

Figure 26 — *Schematic of TWT and power supplies.*

designed together "from the ground up" to insure proper interfaces and a high-quality amplifier for a specific application.

Transmit-receive limiters

Transmit-receive (TR) limiters serve two basic functions. First, they attenuate power entering the receiver during a transmitted pulse to a level which will not harm the receiver or bias it to a temporarily insensitive condition. Second, during receiver on-time, the limiter provides a path of minimum insertion loss, subjecting the receiver to the strongest possible return signal.

Over the last several years, a number of high-pulsed-repetition-frequency radar systems have evolved which require a TR-limiter system that can handle powers on the order of 50 kilowatts, yet display insertion losses of about 0.5 dB and recovery times of less than 5 nanoseconds. This very short recovery time allows monitoring the maximum possible return signal. The Hughes multipactor shown in Figure 27 takes advantage of the principle of multipacting (multiple impacting) to meet these demanding specifications.

Figure 28 shows the relative location of a multipactor TR-limiter system in a simplified radar block diagram. The protective circuit consists of a high-power stage (multipactor) which limits the power to several watts, and a low-power stage (solid-state limiter) which further reduces the power to milliwatts.

Basically, the multipactor section offers protection against three potentially dangerous situations: (1) sharp pulses due to mismatches, (2) high-power arcing at the antenna, (3) the presence of extraneous radar signals.

When the transmitter is on, up to 10% of the transmitted power (50 kW peak) can be reflected due to the impedance mismatch of the antenna. Thus, the multipactor is normally required to limit approximately 5 kW of reflected power to about 8 watts. A more serious limiting problem can occur during transmitter on-time if a high-power arc should develop at the antenna. In this case, up to 80% reflection can occur and the multipactor section must attenuate approximately 40 kW down to 8 watts. In both cases, the limited power is absorbed by the multipacting process and the resulting heat is removed by conduction cooling.

A third limiting process occurs when extraneous radar signals are present. The RF circuit of the multipactor essentially constitutes a bandpass filter. Since the operating band of the multipactor is coincidental with the passband, any out-of-band signals received by the antenna will be reflected and absorbed at port four of the circulator by the dummy load. The multipactor section of the limiter requires no synchronous signal for operation. The first half-cycle of the incident RF wave initiates the multipacting process.

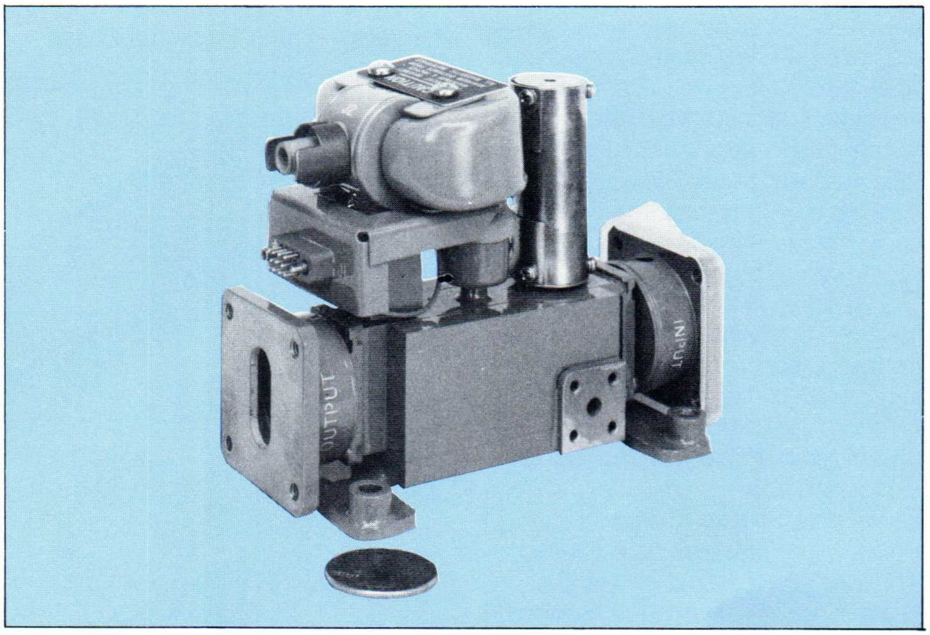

Figure 27 — *Actually a small system, the multipactor limiter operates from unsophisticated power supplies.*

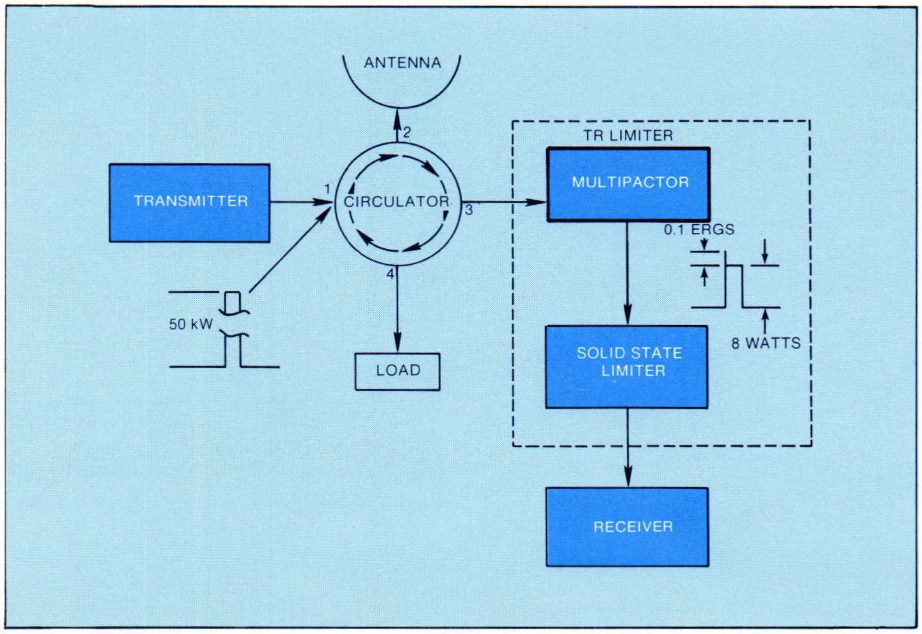

Figure 28 — *Multipactor limiters handle up to 50 kW peak power at X-band.*

How to Evaluate TWTs

The basic considerations in selecting a TWT for a specific application are center frequency, bandwidth, and power output. A number of other parameters must be considered, however, in the specifying process.

Power vs. frequency

When discussing the power capability of TWTs, it is important to make a clear distinction between the peak and average power since these two numbers are limited by totally different considerations. The average power at a given frequency is almost always limited by thermal considerations relative to the RF propagating circuit. The electron-beam focusing is never perfect, and a sizable fraction of the total beam power is intercepted by the RF circuit.

At some point, amenable to calculation, the circuit temperature approaches the melting point of copper, (or the Curie temperature of iron in the case of a PPM TWT). In both cases the tube is close to destruction, and this condition defines the average power capability of that device. Peak RF power capability is closely dependent upon the voltage for which the tube can be designed. The beam current varies as the 3/2 power of the voltage, and the product determines the total beam power.

$$I_{beam} = KV_0^{3/2}$$

where V_0 is the beam voltage.

$$\text{Beam power} = I_{beam}V_0 = KV_0^{5/2}$$

where K is the electron-gun perveance.

With the available techniques for the design of solid-beam electron guns with good optics, the perveance is generally limited to a value not much greater than 2×10^{-6} (MKS units) and most existing power tubes utilize a value between 1 and 2×10^{-6}. Once the perveance is fixed, the required voltage for a given peak beam power is then uniquely determined. This, in combination with practical efficiency values, fixes the peak RF power which the design will support. In turn, the voltage uniquely establishes the circuit parameters. For this reason it can be seen that a TWT can only operate at the design voltage.

Theoretically and practically, these limits for TWTs should be very close to those values which apply to high-power klystrons, since the basic considerations are identical in the two cases. Historically, high-power klystrons came first, and, consequently, most of the early multi-megawatt radars were designed with klystrons as the output amplifiers.

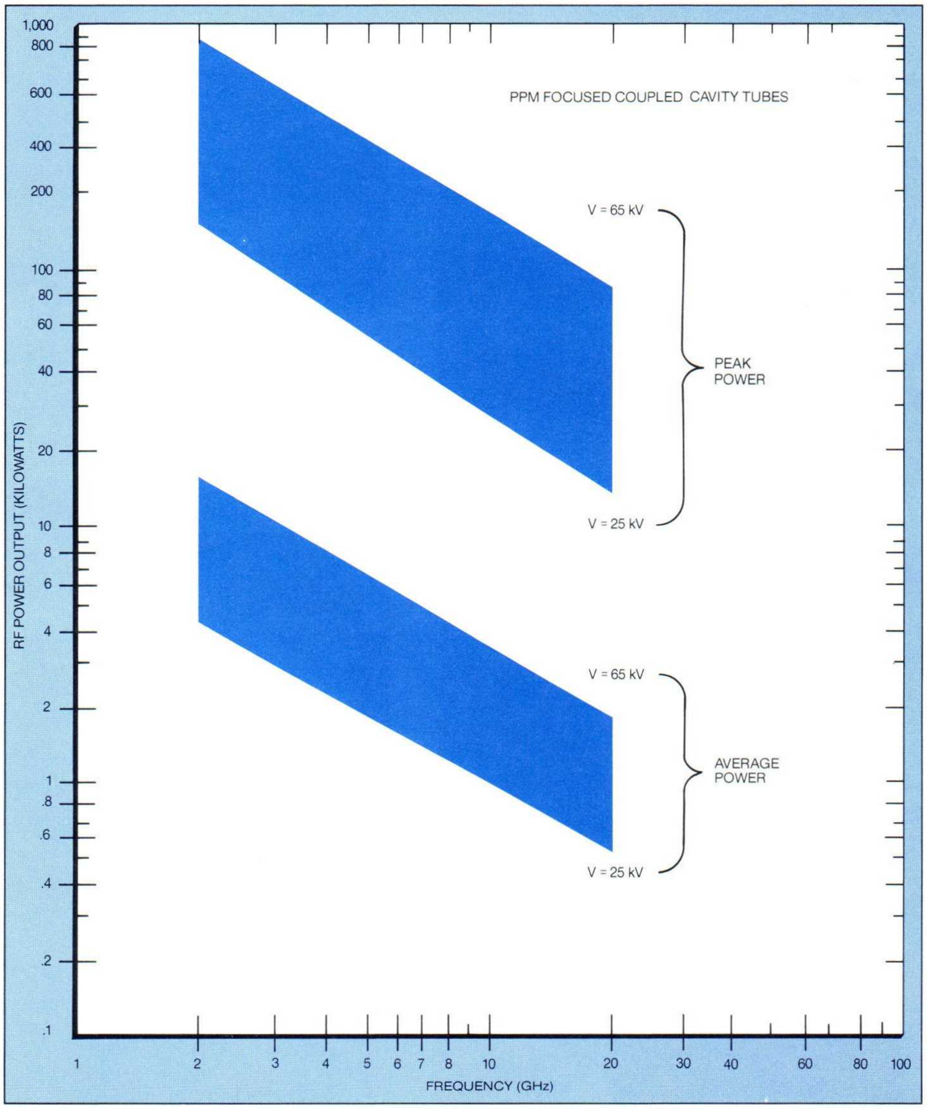

Figure 29 — *Peak-and-average-power capability of typical TWTs in field use.*

There are a few notable exceptions today, but in general, high-power TWTs are available at power levels below 500 kW and voltages below 80 kV. If a requirement should develop for a particular system, there is no reason why a multi-megawatt TWT should not be considered. If, however, available hardware is to be used, probably a klystron or a crossed-field amplifier will be selected.

To give an abbreviated picture of some of the more popular current TWT designs, Figures 29 and 30 illustrate the difference between peak and average power capability and the difference between PPM- and solenoid-focused designs.

The curves follow the general characteristic defined by

power X frequency = constant

which is different from the popular precept of power varying as the inverse square of the frequency.

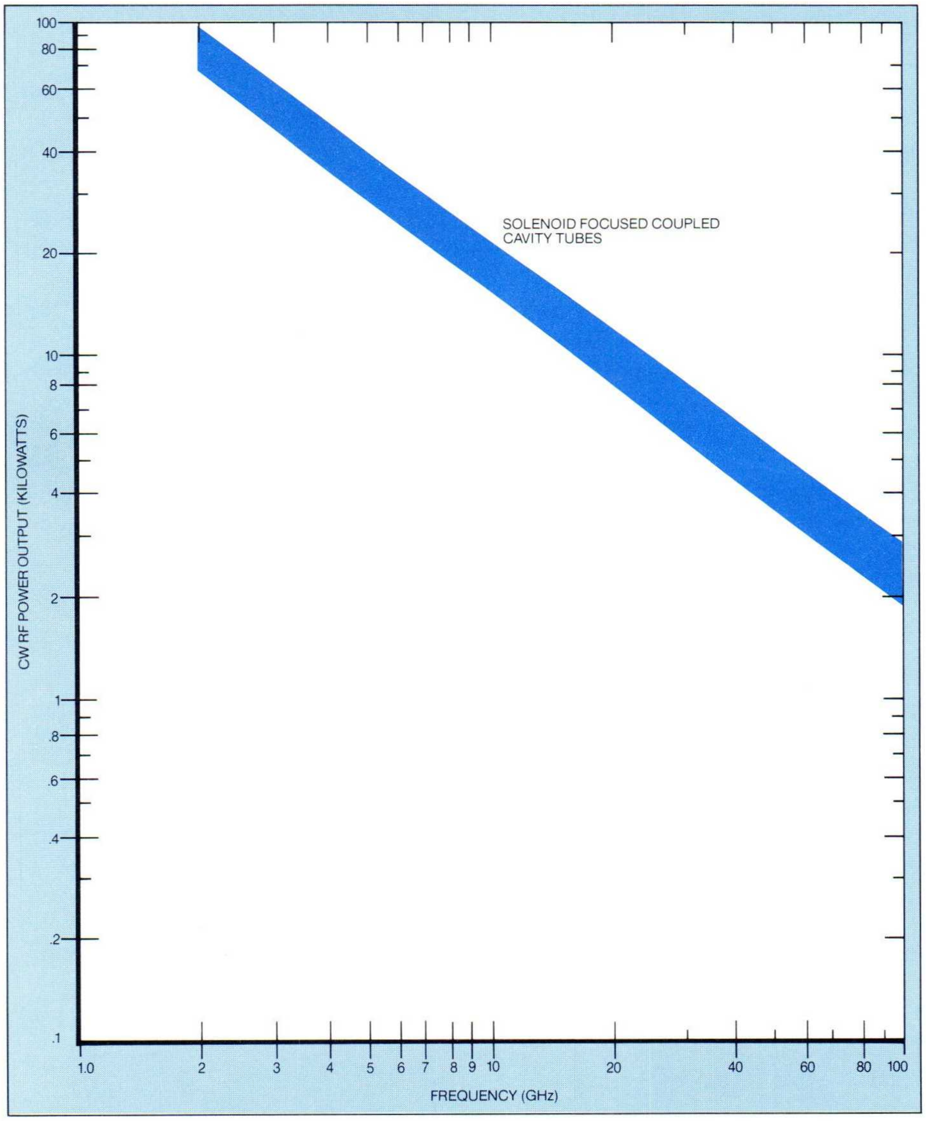

Figure 30 — *CW power capability of TWTs operating at nearly 20 kV.*

Which rule is correct? Both are, but one must be careful how they are applied. If a given design is scaled over a limited frequency range and the thermal stress is to be maintained constant within the circuit, the linear relationship applies. If one desires to scale a particular device to its ultimate limit in terms of power and frequency such that all of the key parameters are pushed to the state-of-the-art (that is, beam density, cathode loading, magnetic field, voltage, etc.), then the quadratic dependency is more appropriate.

It will be noted that if the voltage is increased, the peak and average power capabilities increase considerably. This variation is a direct consequence of the way in which the circuit dimensions and the peak beam power increase with voltage. The larger circuit will accommodate a greater amount of thermal dissipation, and the higher beam power will permit more peak RF power.

At some point the peak RF power will be limited by waveguide arcing problems and voltage breakdown in the electron-gun region. The curves shown go up to 65 kV, which is certainly not the limit, but encompass the great majority of TWTs in field operation.

The CW curve is shown for 20 kV, which is a voltage region representing a good compromise between voltage insulation problems in the power supply and circuit size for reasonable thermal stress levels. The upper boundary of the curve is a conservative design boundary and can easily be exceeded by a factor of two for special applications requiring more average power. Here again, the same rule of power-frequency product being a constant is maintained for the same reasons previously stated. The curve shown does not indicate bandwidth capability, even though this parameter affects average power capability. In general, for very large percentage bandwidths, the average power capability may have to be reduced as much as 50%.

Efficiency

During the early years of TWT development, when the emphasis was on bandwidth, gain, and noise figure, most TWTs were regarded as low-efficiency amplifiers, compared to the more conventional microwave sources such as klystrons and magnetrons.

Industry was slow to change this viewpoint, believing that inherent in the energy transfer process between the electron beam and the RF wave were physical constraints causing the low efficiency. Certainly the experimental evidence from a large number of designs indicated a typical efficiency of 10% or even less. Klystrons at comparable frequencies and power levels gave more than 30% conversion efficiency during the same period in time. The price for large bandwidth capability was thought to be a poor-to-modest efficiency.

Only slowly did researchers discover the key parameters which had to be carefully controlled to significantly improve upon this picture. Improved control of the electron beam trajectories contributed a great deal in changing the situation since the efficiency enhancement achievable with simple depressed collectors was very encouraging. Experimental work became more precise and the data more predictable, allowing theoretical efforts to be evaluated with quantitative results.

Many theories were advanced which presumably should have yielded the same information since they were all based on the same physics. However, considerable disagreement existed, mostly because investigators could not obtain repeatable experimental data. In the last few years, great progress has been made to eliminate this confusion, and real advances have been achieved in efficiency enhancement. The 50% efficiency barrier has been broken a number of times and, like the 4-minute mile, this is no longer regarded as an upper limit dictated by nature.

There are two fundamental mechanisms whereby increased efficiency can be realized in a TWT amplifier. The first mechanism is collector depression, or a series of collectors which can be depressed well below the circuit potential so that unused energy can be recovered from the spent electron beam. Such a collector must be carefully designed optically so that an excessive part of the beam is not turned around and deposited on the circuit.

The optics of such a system are quite complicated and depend not only upon the geometry of the collector segments, but also upon the degree of RF modulation, the magnetic field used to focus the beam, and the relative potential of the circuit and all the segments of the collector.

The main advantage of working with the collector to enhance the overall efficiency is that such an alteration does not affect the circuit of the TWT and can, therefore, be accomplished independently of the RF design of the tube. The power supply, of course, must be properly designed to take advantage of the energy recovered by the depressed segments of the collector.

The second mechanism of efficiency enhancement is sometimes referred to as velocity resynchronization. It is well known that the electron beam slows down in velocity when it gives up energy to the amplified RF wave on the circuit. As a result, the propagating wave and the electron beam progressively lose synchronism, with the wave moving far ahead of the beam. When this occurs, the electron bunches are no longer favorably phased to give up energy to the moving wave, and the amplification process ceases before maximum signal level is achieved.

External measurements merely show a lower efficiency than that which one might reasonably expect. Early models of TWTs almost always gave disappointing efficiencies because of this unfavorable condition within the tube's interaction region.

First-order corrections for a lack of synchronism between the beam and the wave can be done with a mere increase in the operating voltage. Unfortunately, this step causes the amplification process to suffer in the small-signal region (near the input) of the circuit, and it also causes the linearity of the output versus input curve to degrade. It would appear that an easy solution to this problem would be to make the RF wave velocity on the input circuit different from that on the output circuit such that synchronism could be maintained everywhere.

This simple concept resulted in the "tapered velocity"-type circuit, which is one of the basic tools that the TWT designer now frequently employs. In practice, there is an infinite variety of tapers that differ in the degree of velocity change and the variation of velocity as a function of distance along the slow-wave structure.

Determining a satisfactory configuration requires the use of a large-scale computer to simulate the nonlinear interaction process between a stream of highly bunched electrons and a growing electromagnetic wave propagating along the circuit. Any choice must be a result of a series of compromises which trade one desirable effect for another.

Some of the considerations are based upon second-order effects that are extremely difficult to evaluate quantitatively, and yet collectively these effects are quite important. A great amount of controversy still exists among the experts as to precisely what represents the optimum solution.

Some disagreement will always exist, because the desired performance depends upon the user's requirements in terms of complexity and the criticality of the adjustments. Even more important is the required bandwidth, since for ECM systems, octave bandwidths are quite common. Over such an extreme bandwidth, the important electrical parameters, which are proportional to wavelength, change by a factor of two or more. It is not surprising that optimum conditions within the velocity taper region are impossible to maintain.

In spite of this problem, recent results from efficiency enhancement schemes for ECM power amplifiers are indeed impressive and perhaps would cause one to doubt the difficulty of meeting all of the criteria in the taper design. Figure 31 illustrates the efficiency of a kilowatt helix-type high-gain ECM TWT. It should be noted that the frequency coverage is 1½ octaves with an efficiency above 45%.

An example of the performance obtainable with velocity resynchronization is shown in Figure 32 where the efficiency of a coupled-cavity tube is shown to be in excess of 50% over the entire operating band. This particular form of velocity resynchronization was achieved with a "voltage jump" whereby the beam near the output of the circuit is accelerated by a boost in the operating voltage. Although simple in concept, this scheme is quite difficult to implement in a practical high-power tube where the operating voltage is high. The output circuit boost was 8 kV in the example illustrated, which means that excellent insulation must be provided without disturbing the RF propagation characteristics of the structure. In a helix tube, where the circuit is a continuous-wire conductor, a voltage discontinuity is very difficult to accommodate because of RF reflections from the break, while in a coupled-cavity circuit, the outside boundary of the cavity walls is generally grounded, which creates an insulation problem. Figure 33 is a schematic drawing of the cross-section of the circuit of the TWT showing how the voltage-jump isolation was accomplished.

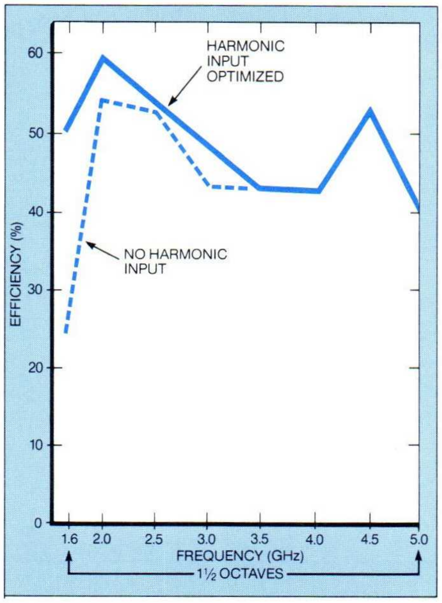

Figure 31 — *Broadband high-efficiency TWT.*

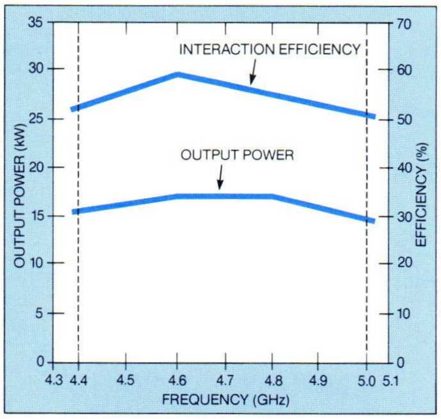

Figure 32 — *High-efficiency coupled-cavity TWT.*

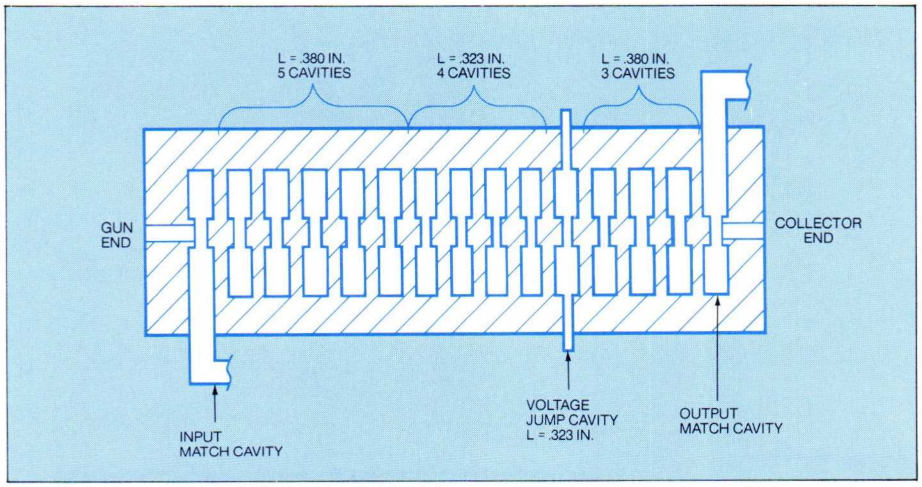

Figure 33 — *High-efficiency voltage-jump TWT.*

Harmonic injection

Another method of efficiency enhancement, unique to broadband helix devices, does not involve any alterations of the internal parts of the TWT.

It is generally referred to as "harmonic drive" because it is associated with special adjustments made to the second-harmonic content of the input RF signal. The solid portion of the curve of Figure 31 shows the additional enhancement which is afforded with "harmonic drive."

The phenomenon was discovered quite some time ago when it was observed that the wrong type of second-harmonic input would seriously degrade the power output at the fundamental frequency. On the other hand, the correct amount of second harmonic, properly phased, will increase the fundamental power output and suppress the second harmonic at the output of the amplifier.

This process is one of cancellation, whereby the injected second-harmonic signal is such that it is 180° out of phase with the second-harmonic signal generated by the nonlinear processes inherent in the interaction mechansim. With careful design of the input circuit, this cancellation can be made reasonably noncritical and quite broadband.

The effect is only important at the low end of the tube's amplification band since the second harmonic of these frequencies still lies within the amplification band of the TWT. Above midband, there is no appreciable amplification of the second-harmonic signals, and, consequently, the enhancement scheme is not effective above this point.

To provide the correct harmonic input signal, a simple circuit consisting of a phase shifter and a microwave diode can be utilized to transform a pure drive signal to one with a significant second-harmonic component. If the drive signal emanates from an overdriven TWT (one operating well into saturation), it is quite likely that the second-harmonic portion is large to begin with and of the wrong phase. It is difficult to compensate for such a drive signal since the adjustments will be generally quite critical and subject to change as the drive level changes.

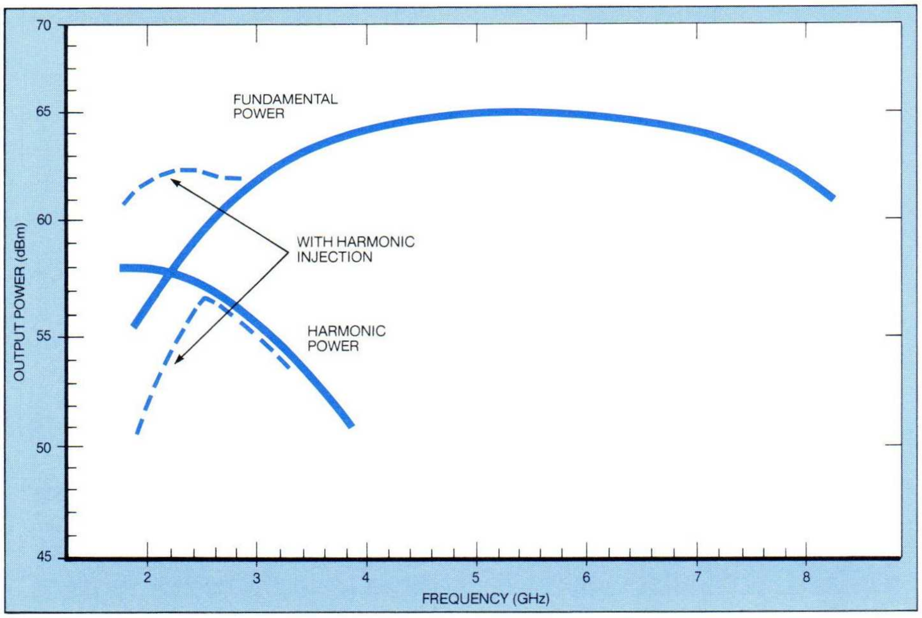

Figure 34 — *Fundamental and harmonic output power of wideband helix tube with or without harmonic injection (measured).*

Harmonics

Due to the wide bandwidth and high gain of the TWT—plus the fact that in saturation, the tube acts as a non-linear device—there will be harmonics in the RF output spectrum. Typically, at saturation for a narrowband application, the second harmonic will be 8 to 10 dB below the fundamental signal. However, very broadband devices will have a higher second-harmonic content.

Other higher-order harmonics will also be present to a lesser degree. The harmonic magnitude is a function of the fundamental frequency and bandwidth range, with the lower band edge signals having the greater effect.

The harmonful effects of harmonic interaction in multi-octave TWTs can be minimized by injecting a coherent harmonic signal at the input of the tube, simultaneous with the fundamental signal.

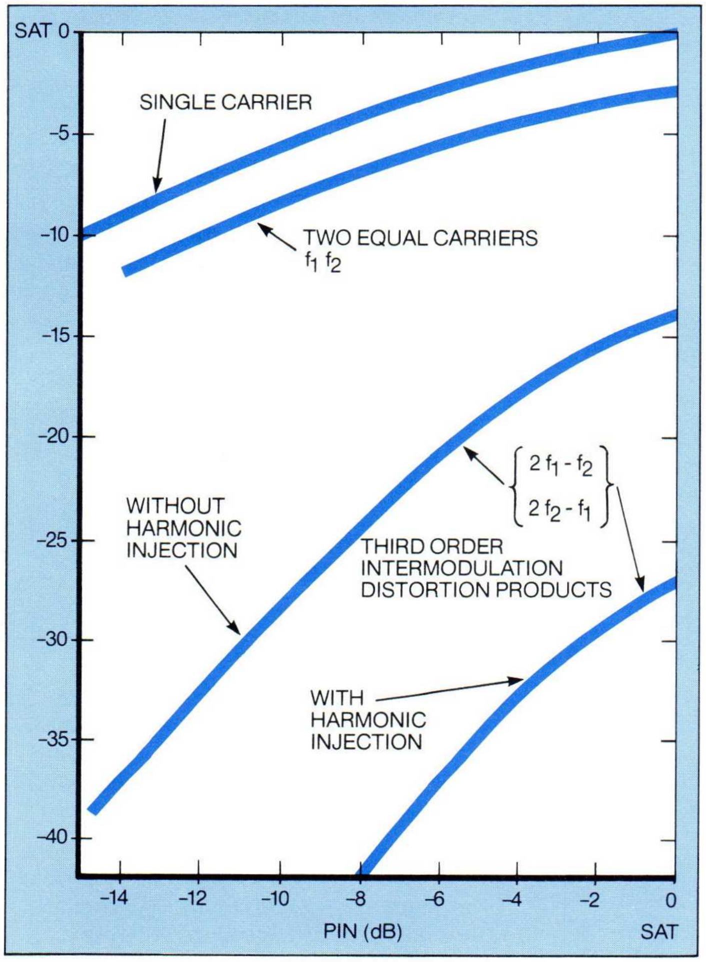

Figure 35 — *Third-order intermodulation distortion with and without harmonic injection (measured with two equal carriers).*

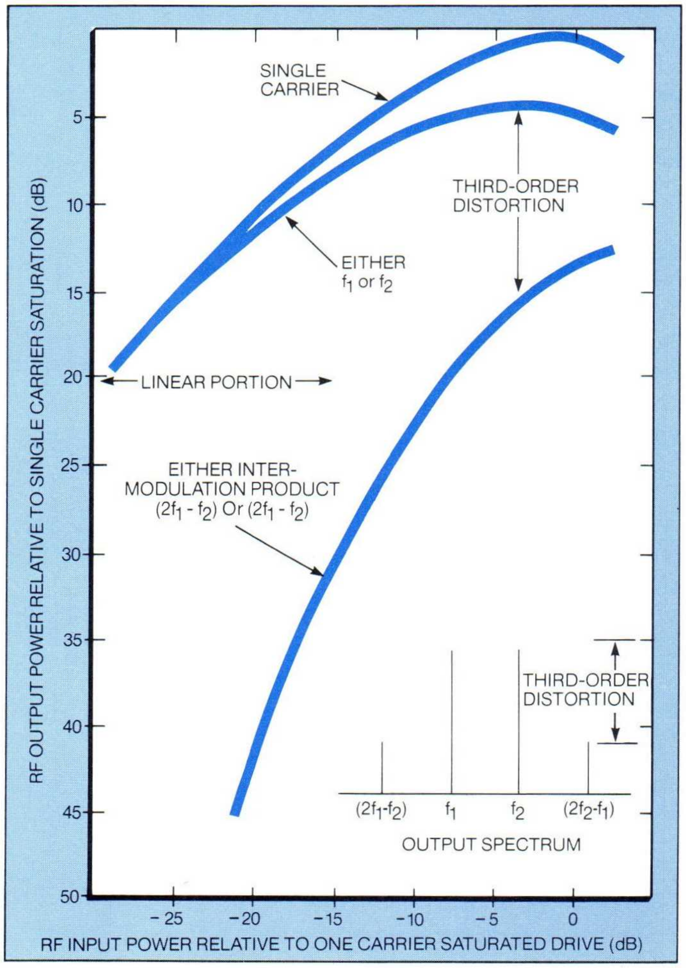

Figure 36 — *Typical third-order intermodulation data for Intelsat IV type TWT.*

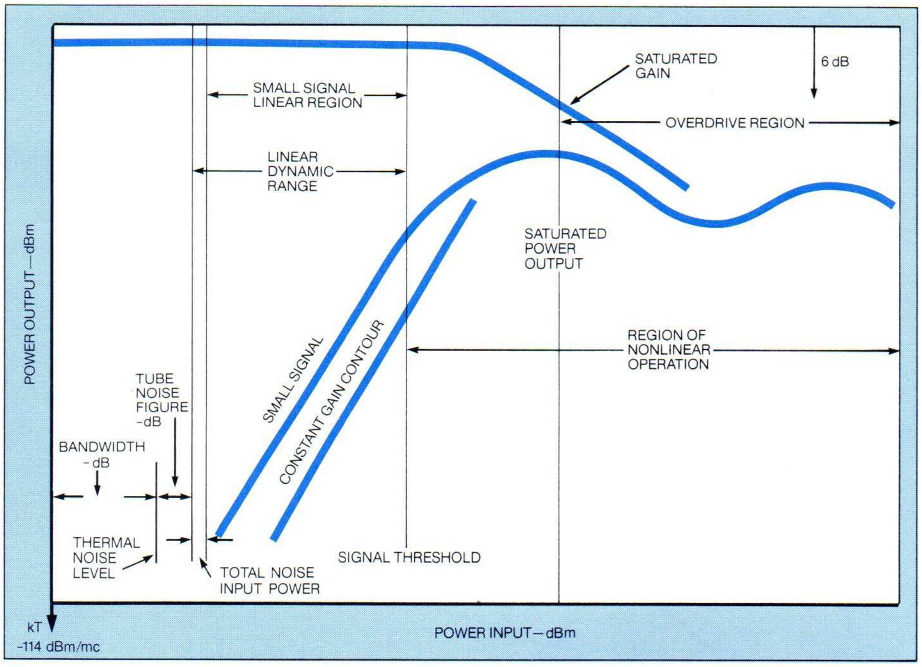

Figure 37 — *Dynamic characteristics of the traveling-wave tube.*

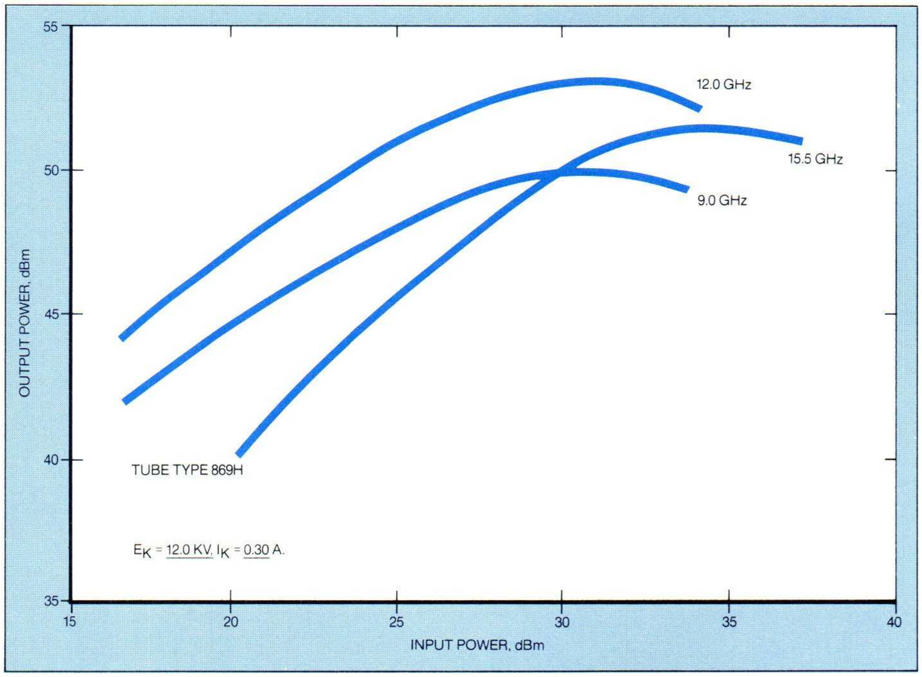

Figure 38 — *Transfer characteristic.*

When the phase and the amplitude of the injected harmonic signal are optimized, the degrading effects of harmonic interaction can be minimized—resulting in an efficiency enhancement at the fundamental, as well as a reduction of the harmonic output power and an improvement in intermodulation performance. All of these effects are shown in Figures 34 and 35. The coupled-cavity circuit, due largely to its filter-type characteristic, has less harmonic content in the output signal. The harmonic content of these tubes is seldom greater than 20 dB below the fundamental.

Intermodulation distortion

When more than one carrier is introduced at the TWT input, a mixing, or intermodulation (IM) process, takes place. This results in intermodulation products which are displaced from the carriers at multiples of the difference frequency.

The power levels of these intermodulation products are dependent on the relative power levels of the carriers and the efficiency of the TWT. In the case of two balanced carriers, Figure 36 shows the variation of carrier and IM product power level with total drive power. The single carrier power curve is also plotted for comparison. As in the case with AM/PM conversion (see below), the IM distortion is significantly reduced in the small-signal (linear) region of the RF drive range. For this reason, communication TWTs are normally operated well below their saturation power level.

Transfer curves

The drive characteristics of an ideal TWT are shown in Figure 37. The threshold of useful operation is determined by the bandwidth and noise figure of the tube. The dynamic range is that region between the threshold input level and the input at which there is departure from small-signal or linear gain. The gain continues to decrease for approximately 6 dB to the point of saturated power output.

The overdrive capability of a TWT indicates the range over which the output power will remain in the saturation region as input is increased. When further input is applied, output power decreases. For certain applications, it is desirable to maintain full or saturated power output over a broad range of input signal conditions. Limiter actions to achieve this objective are in the design of the RF structure, use of multiple attenuators, and cascading two TWTs with additional equalizers and isolation filters.

Figure 38 shows the transfer characteristics of the Hughes 869H for three frequencies within the band.

AM/PM conversion

Amplitude modulation/phase modulation (AM/PM conversion) is defined as the change in phase angle between input and output signal as the input signal varies. This factor is measured dynamically and is expressed in degrees per dB at a specified value of power output.

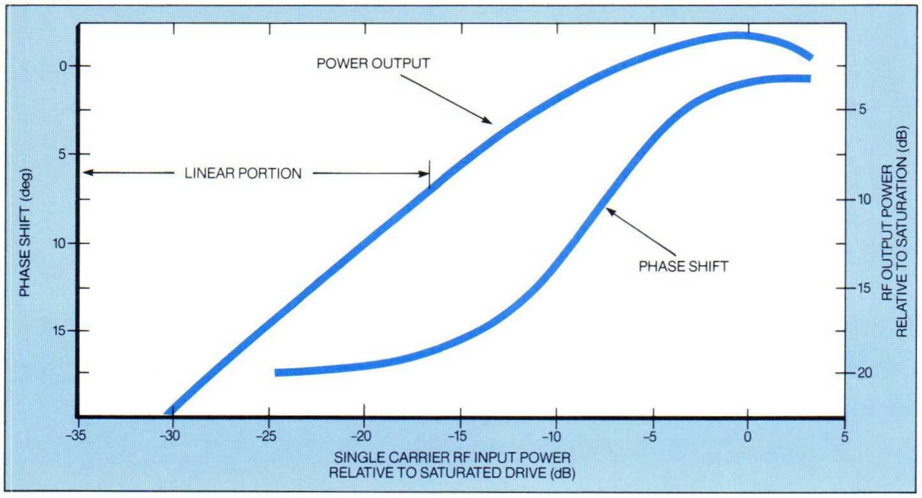

Figure 39 — *Typical power output and phase shift as a function of RF input power for a communications type TWT.*

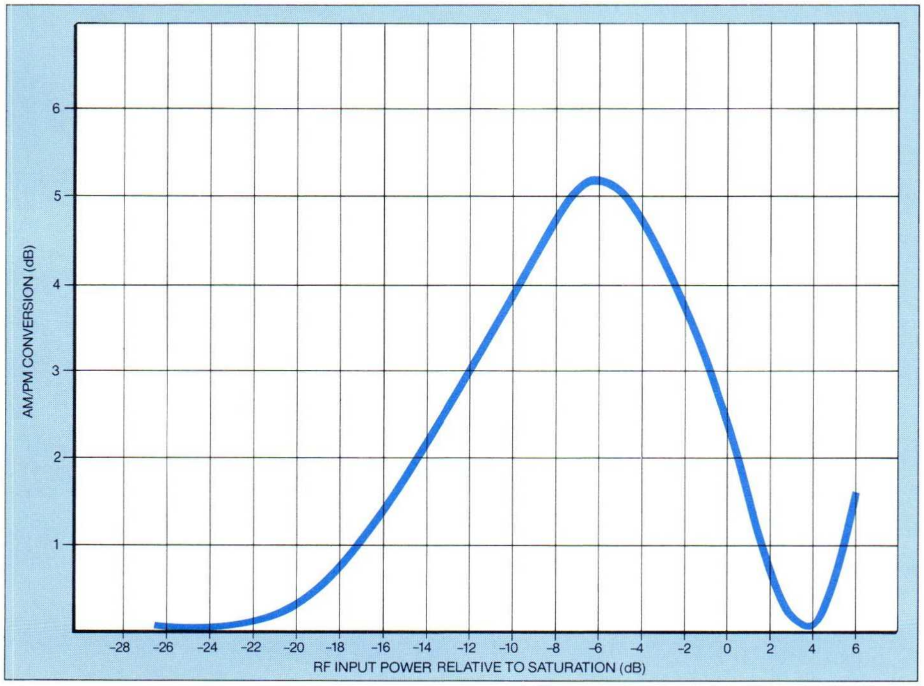

Figure 40 — *For a single carrier condition, AM/PM conversion rises sharply as drive is increased.*

AM/PM conversion in a TWT is due to the reduction in beam velocity as the input signal level increases, causing a greater energy exchange between the beam and the input RF wave. At a level 20 dB below the input required for saturation, AM/PM conversion is negligible. Beyond this point, AM/PM conversion increases sharply.

A typical power output and relative phase shift characteristic is shown in Figure 39 for a TWT. Here it is seen that phase shift is relatively insensitive to drive in the small signal ("linear") portion of the RF output power characteristics. As the TWT is driven into saturation, the rate of phase change increases and then decreases as the power saturates. The slope of this line, or AM/PM conversion, is plotted against RF drive in Figure 40.

The peak AM/PM generally occurs at a drive level 3 to 10 dB below saturation drive and is frequency dependent. The value of AM/PM conversion is less at the low-frequency end of the tube's passband than at the high-frequency end. The curves show typical performance at the high end of the band, which is, of course, the worst case.

The information in the charts applies to the case of a single carrier. For two or more carriers, transfer takes place, giving PM at the output on one carrier due to AM at the input on the other. The general trend with drive is similar for this case, but the specific values are different and are also a complicated function of the relative carrier amplitudes.

Phase sensitivity

Any factor which affects the velocity of the electron beam will give rise to phase changes in the RF output signal. If the disturbing factor varies with time, then the result will be phase modulation of the input RF signal. The primary factors affecting the velocity of the beam are cathode temperature, magnetic fields, grid voltage, anode voltage and cathode voltage.

The power supply designer must take into consideration these phase-pushing factors when designing the power supplies for a TWT, since the system noise requirements will dictate the power supply ripple and stabilities that must be maintained. Typical values for TWTs are:

35 degrees per 1 percent change in cathode voltage,
5 degrees per 1 percent change in grid drive,
2 degrees per 1 percent change in anode voltage,
.01 degrees per 1 percent in filament voltage.

These values should be considered as order of magnitude since the actual value for any specific tube will be a function of many factors such as type of circuit, gain, perveance, etc.

Phase linearity

Phase linearity is normally expressed as either group delay or as a deviation from linearity in degrees.

The phase-versus-frequency characteristics of a TWT are related to the transit time of the RF signal traveling from the input to the output of the tube. Non-uniformities within the tube give rise to phase ripples which are magnified as a result of reflections both within and external to the tube. To minimize phase perturbations, it is necessary to have a low VSWR for both the source and load. In addition, it is necessary for the tube designer to achieve not only a uniform circuit characteristic but also extremely good matches within the tube when internal severs or terminations are employed.

The slow-wave structure for helix tubes is normally quite uniform without any abrupt discontinuities. The use of computer-controlled machines to fabricate the slow-wave structure has helped to perfect this uniformity such that phase flatness (group delay) can be held to very tight tolerances.

Since the slow-wave structure of a coupled-cavity tube is composed of discrete elements and the termination is more abrupt, phase linearity is much more difficult to achieve.

For applications requiring flat phase response, Hughes has developed a patented technique. Employing this method, Hughes has achieved group delays of less than 1.5 nanoseconds peak to peak.

Phase tracking

In many systems a requirement exists to operate TWTs in parallel. In this type of operation it is important that the phase variations of those tubes operated in parallel are as close as possible to being identical.

It is not so important that the total phase shift through the tubes be the same, since a phase shifter can be employed to adjust the phase delay through the tubes at any particular frequency. It is important, however, that the variation over the frequency band of interest be similar.

Helix TWTs can be designed to have tube-to-tube phase tracking of five degrees or less, provided care is taken to minimize reflection effects and fine grain variations. It is more difficult to maintain close phase tracking in a coupled-cavity tube, and variations of between 10 and 15 degrees are to be expected.

Noise figure

The noise figure (NF) expressed in dB is a measure of the degradation in signal-to-noise (S/N) ratio with passage of the signal through a given tube and can be expressed as follows:

$$\mathrm{NF} = \frac{\text{Input S/N}}{\text{Output S/N}}$$

The primary source of noise in a TWT is related to the density and electron velocity variations within the electron beam. The level of the noise power is related to the number of electrons and the size of the electron gun and its beam optics.

For medium power (10 watts) tubes, the NF is typically 30 to 35 dB and increases with power and frequency.

Noise power output

For some applications the noise power output (NPo) is of prime importance and may be measured by terminating the input and measuring the NPo at the output of the TWT. The NPo can be calculated from the following equation with all parameters stated in dB:

$$\mathrm{NPo} = -114 + (\mathrm{BW}) + (\mathrm{Gss}) + (\mathrm{NF})$$

where:

−114 dBm/MHz Thermal Noise with input terminated

BW = System bandwidth and can be determined from the following table:

BW (MHz)	dB
1	0
10	10
1000	30
2000	33

Gss = Small Signal Gain

NF = Noise Figure

Due to the broad-band nature of TWTs, the measured NPo is much greater than calculated; therefore, to determine a realistic NPo the noise figure-gain product should be integrated across the total bandwidth.

Dynamic range for linear operation

The linear region is defined as the limit of linear operation at the point where increasing the RF input signal results in a gain compression of 1 dB. (See Figure 41.) This point is called the 1 dB compression point. Therefore, the dynamic range for linear operation may be defined as the ratio of this maximum input signal to the reference noise level of the TWT.

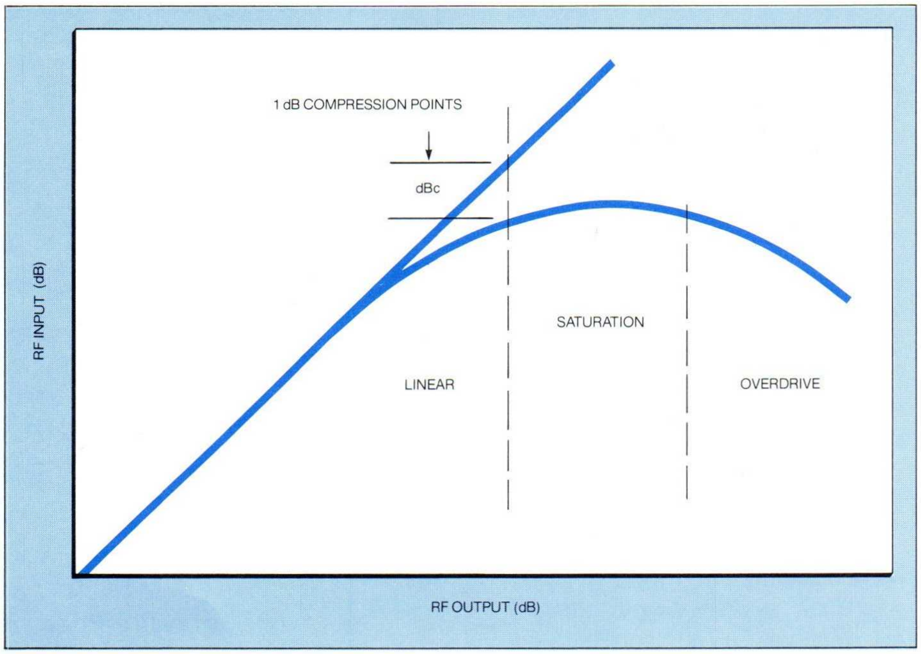

Figure 41 — *RF output dB.*

Spurious outputs and stability

Spurious outputs are minimized and stability is assured through proper designs of the electron beam optics and magnetic focusing. In addition, the processing and fabrication of the TWTs must be carefully controlled. Spurious oscillation is eliminated or minimized by oscillation suppression techniques, such as special attenuation patterns on the support rods of helix TWTs and loss buttons (Hughes' patented technique) in coupled-cavity TWTs. These techniques effectively suppress the tendency to oscillate at the circuit mode edge and render a given TWT completely stable over a wide range of operating voltages.

Relative to the stability of a complete amplifier (TWTA), the beam (cathode) power supply is of great importance. This supply determines the velocity of the electron beam which affects the stability of the TWT.

Reliability/life

Traveling-wave tubes have, over the years, gained a reputation for high reliability and long life. There are many factors that affect these parameters, such as the basic design, the interface, protective measures, handling, installation/operation and storage.

Basic design

The most important factor relative to life is the type of cathode and the cathode loading factor. In addition, special attention must be paid to electrode size, shape and spacing. The method of packaging must meet the vibration and shock requirements for the application. And to meet wide temperature ranges and high altitude (space) requirements, consideration must be given to the cooling technique; i.e., conduction, liquid, air, heat pipes, etc. Potting and conformal coating must ensure an arc-free and nearly corona-free device.

Interface

The operation of TWTs must be confined to the limitations of the operating and environmental parameters for which the tube was intended. Some of these parameters can be eliminated and the interface effort minimized by taking advantage of the "black box" concept; i.e., TWT and power supply are built by Hughes and supplied as an integrated unit. This approach limits the interface to the drive signal, RF input and output loads, and input voltage.

Protective measures

Steps must be taken to provide protective measures so that the TWT is not exposed to abnormal extremes, such as voltage surges, temperatures, load mismatches, system arcs, and loss of cooling. All TWTs and TWTAs are supplied with operating instructions and test performance data. Special attention should be given to the recommended precautions and operating instructions.

Handling

Careful handling of the TWTs during shipment and installation is advisable so that the exposed high-voltage connections, ceramic seals and RF connectors are not damaged.

Installation/operation

Care must be taken during installation so that no strain is put on the RF connectors. On TWTs with SMA connectors, precautions should be exercised as to the amount of torque applied to the connectors. The waveguide mating flanges should be clean, smooth and flat so that a good mechanical, as well as RF connection, can be made. Polarity of the applied voltages and the direction of cooling liquid or air flow require cautious observation.

Storage

If at all possible, the original shipping container should be retained and used for storing the TWT and for any future handling or moving which may be required. Liquid-cooled TWTs must be free of coolant prior to storage. In addition, the specified storage temperature limits must not be exceeded.

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  - ☐ Ground Terminal TWTAs
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Radar Applications

Although a German scientist, C. Hulsmeyer, patented the first primitive radar as early as 1904, it wasn't until the mid-1930's that practical systems evolved. Early systems employed smoothbore and, at a later date, cavity magnetrons. Today, a wide variety of microwave tubes are employed, including magnetrons, cross-field devices, klystrons, twystrons —and TWTs.

Increasing the range

As radar systems have evolved and grown more sophisticated, the need has developed for higher average power devices to detect targets at greater ranges —even in the presence of ECM interference. And because tracking capabilities have often been equally important, or duty cycles have had to be limited, peak-power requirements have also increased.

The coupled-cavity TWT has proven to be an ideal device for many high-power radar systems. Such tubes are used in mobile, naval and airborne radars. The coupled-cavity tube can provide peak powers in the order of hundreds of kW's at Kμ-band and megawatts at S-band. With solenoid focusing, average powers of as much as 10 to 20 kW's are achievable at Kμ-band and as much as 60 to 80 kW's at S-band.

Bandwidths of 10% are common for coupled-cavity tubes (bandwidths up to 30% are achievable, employing special designs). This bandwidth is sufficient for most systems employing frequency-hopping or frequency-scanning modulation techniques.

Pulse compression

Pulse compression systems require that the phase linearity of the transmitter be extremely good. Although good phase linearity can generally be achieved in helix TWTs, a coupled-cavity tube must be carefully designed to achieve flat phase performance. To accomplish this, Hughes employs a patented technique to introduce in-band loss. Deviations from phase linearity of only a few tenths of a degree in bandwidths of 40 to 50 megahertz have been achieved.

Phase linearity, if held to reasonable limits, will also enable the tube manufacturer to offer TWTs which closely track in phase between tubes. This is of primary importance when tubes are to be operated in parallel. Many systems are being configured using two to four tubes—both helix and coupled-cavity—in parallel. Hughes has an excellent understanding of the tube design constraints which must be employed to achieve good phase tracking in both types of tubes, and for this reason the company is in a position to work closely with the radar designer to achieve the system requirements.

For airborne radar applications, Hughes has employed a solenoid wrapped directly on the tube body. This technique minimizes the size and weight of the TWT, and also reduces the solenoid power. The technique, although first employed for airborne tubes, is now standard practice at Hughes for all new solenoid-focused TWTs.

Higher average power

In a system operating with a high pulse repetition frequency, the total average power can be limited by grid heating. Early TWTs were equipped with a single grid, and the intercepted current could cause the grid temperature to rise to the point at which the grid would start to emit or ultimately fail. Hughes Aircraft Company pioneered the use of the "shadow grid" (see Section 6) for applications requiring a high average power.

There are actually two grids in these tubes. The grid closest to the cathode is very carefully placed directly in front of the second or control grid and is held at cathode potential. Electrons are not attracted to this shadow grid, but its presence in front of the control grid reduces, by an order of magnitude, intercepted current on the control grid—allowing much higher average power to be controlled without excessive grid heating.

Shadow grids are employed in virtually all gridded tubes at Hughes. And even more effective techniques are currently in the development phase. The new techniques promise even further improved tube life and performance.

An Optimum design

TWTs have many peculiarities which must be understood to be certain that system performance will not be compromised. It is important, therefore, that the radar system designer work closely with the tube engineer so that the radar performance is optimized. Among the potential problems:

- Because the tube turns on in a nonlinear manner, some dc pulse compression occurs. This could create a range error.
- The RF saturation characteristics of a TWT are not the same across the frequency band of the tube. This could also create a range error.
- An inductance in the grid lead can result in a triode-type oscillation—which might take months to resolve.
- Long pulses can result in ion-oscillations. Extra tube processing could alleviate this effect.

Other problem areas could be listed. The important point, however, is that the Hughes technical staff, which has designed and built more TWTs for radar than any other group in the world, can help to anticipate difficulties *before* they occur, shortening the design cycle and increasing the chances for ultimate success.

Electronic Countermeasures

Electronic warfare has been defined as a military action to take advantage of the enemy's use of the electromagnetic spectrum or deny its use to him. It is usually categorized into:

ESM (Electronic Support Measures) —Actions taken to search for, intercept, locate and identify enemy emitters.

ECM (Electronic Counter Measures) —Deliberate jamming or deception of an enemy emitter or receiver.

ECCM (Electronic Counter Counter Measures) —Action to ensure effective use of our equipment despite enemy jamming.

The earliest use of RF jamming was in World War I by the German Navy. However, these primitive tactics were not really developed until the military began using radar just prior to World War II.

The development of radar was rapidly followed by the introduction of ECM techniques to deceive and jam them. In turn, the evolution of new radars has been partially the result of a continual need to stay ahead of any new countermeasure tactics which might compromise the radar's effectiveness.

The trend in search radar, for example, has historically been toward much higher powers and techniques that will increase target visibility even while being jammed. A good anti-jamming radar necessarily must be able to shift frequency over a wide bandwidth quickly to avoid the jammer's source frequency.

ECM trends have also been toward wide bandwidth system capabilities. The jammer on the target may be designed to amplify wideband noise, or to deceptively retransmit the hostile radar pulse to offset the radar's ability to determine the target's position.

Because wide frequency bandwidths are essential to the employment of such ECM tactics, an amplifying device capable of broad operating ranges with sufficient output power and efficiency has been needed.

The TWT has proven to be ideally suited for this task. Unfortunately, however, ECM is usually not designed as an integral part of the airframe, but rather adapted internally or mounted in pods externally,

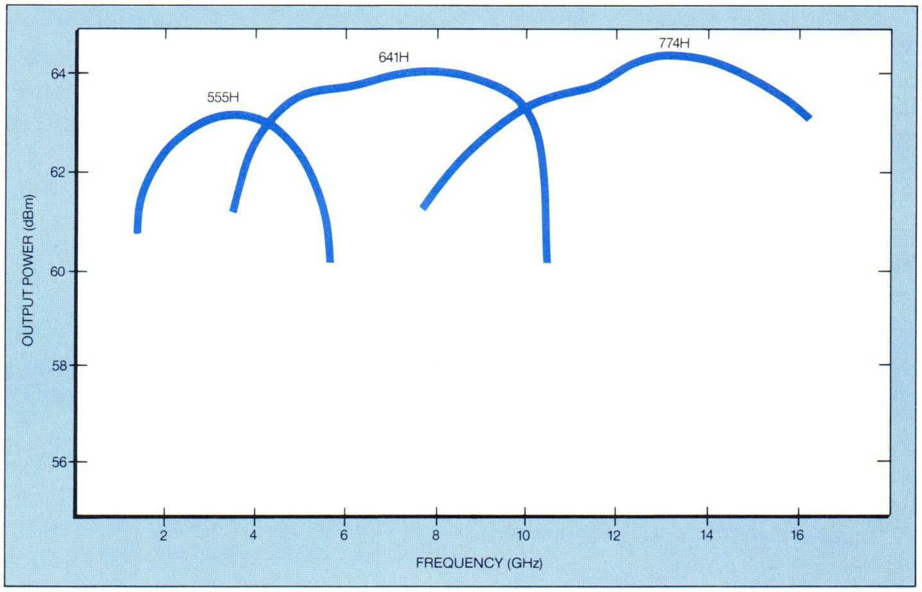

Figure 42 — *The 2 to 18 GHz ECM band is covered with several pulsed helix TWT tubes using single gridded electron guns, PPM focusing and coaxial couplers.*

depending on the military service tactics. As a consequence, TWTs are not standardized with respect to interface parameters and require close liaison between the TWT supplier and the ECM system engineer.

Pulsed TWTs

Hughes Electron Dynamics Division has been a leading supplier of broadband, kilowatt-level, helix TWTs for many ECM systems. Proven production capability has been established with tubes in all the major frequency bands.

Currently, pulsed kilowatt TWTs cover the ECM spectrum up to 18 GHz. Figure 42 shows summary RF output data for typical octave-bandwidth pulsed helix tubes which have been used in conventional ECM systems. The tubes feature a rugged metal-ceramic construction suitable for airborne or missile environments, and typically use a single-gridded electron gun, PPM-focusing and coaxial couplers.

Hughes broadband helix TWTs have proven to be reliable building blocks for many ECM applications. Some typical examples of helix TWTs can be seen in Figures 43 and 44.

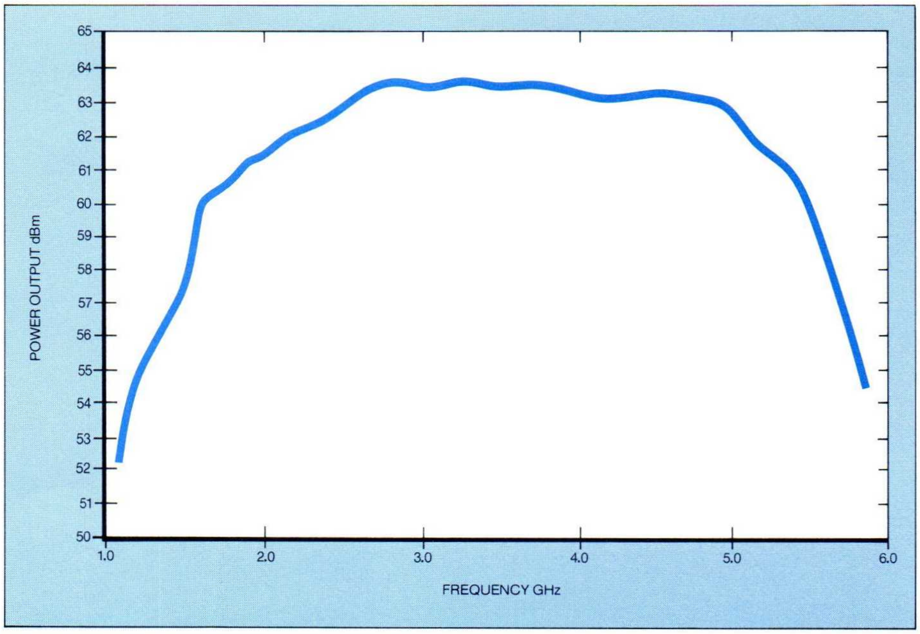

Figure 43 — *Wideband performance fundamental output power vs. frequency.*

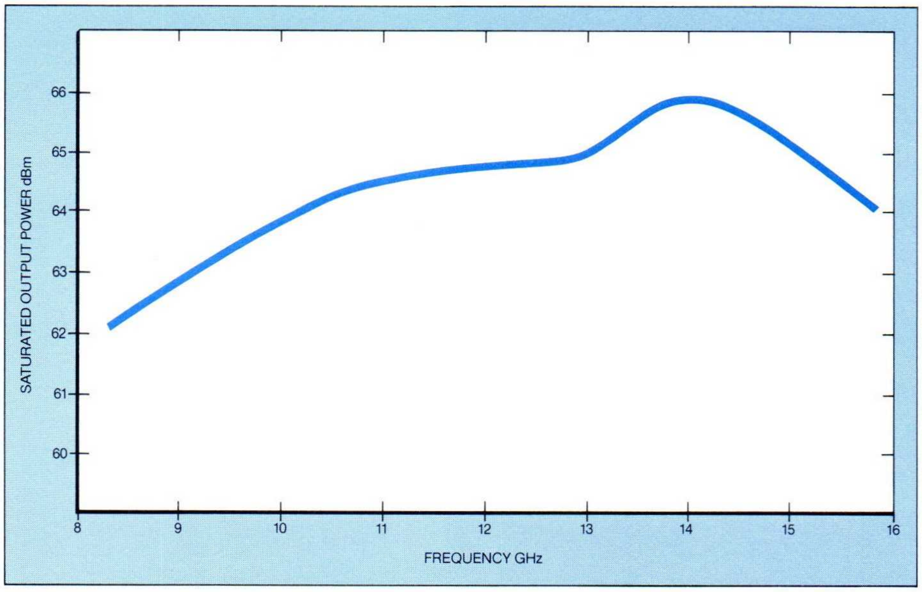

Figure 44 — *774H saturated output power.*

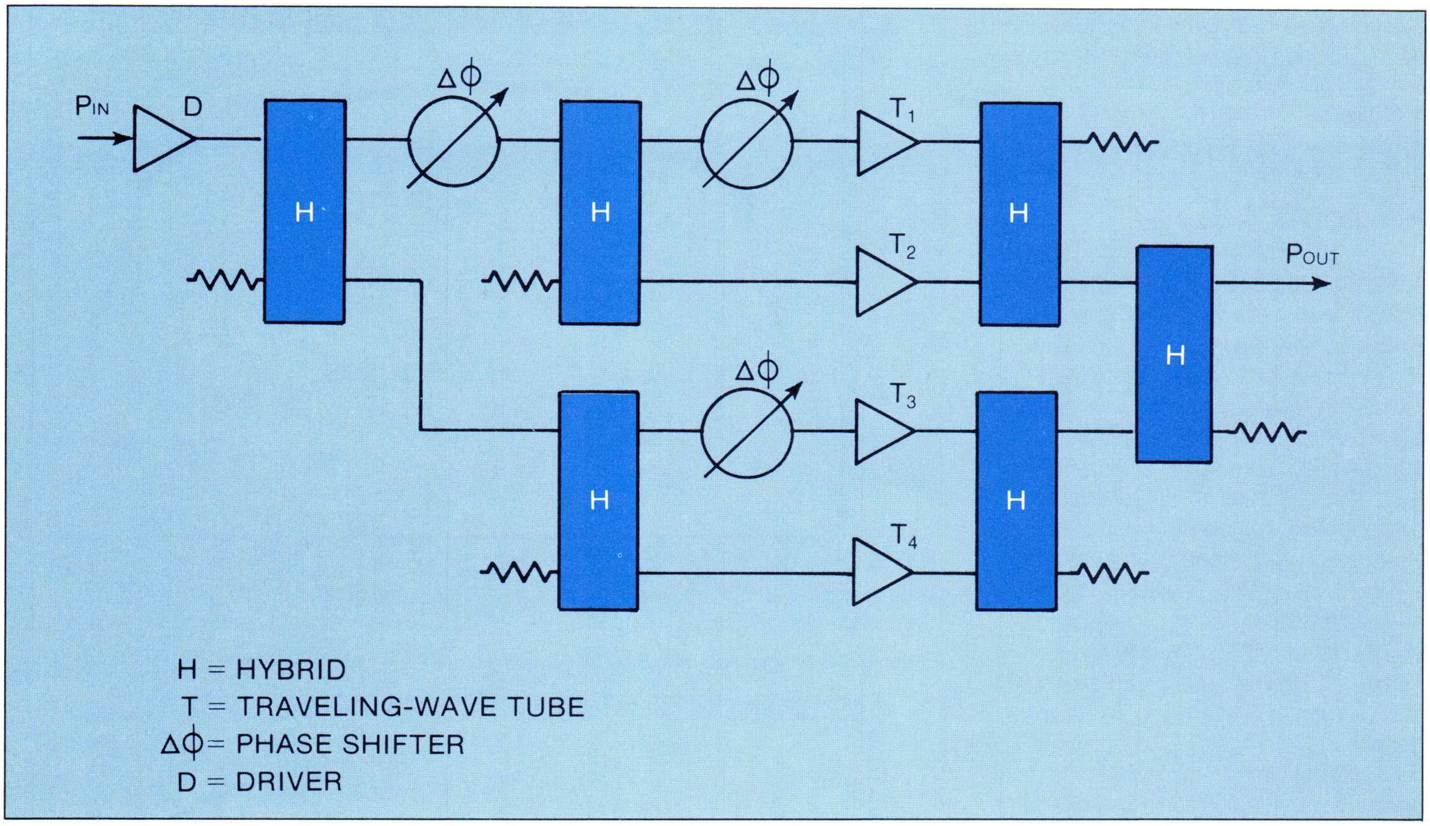

Figure 45 — *When combining several kilowatt-pulsed TWTs to attain higher output, accurate phase tracking is critical.*

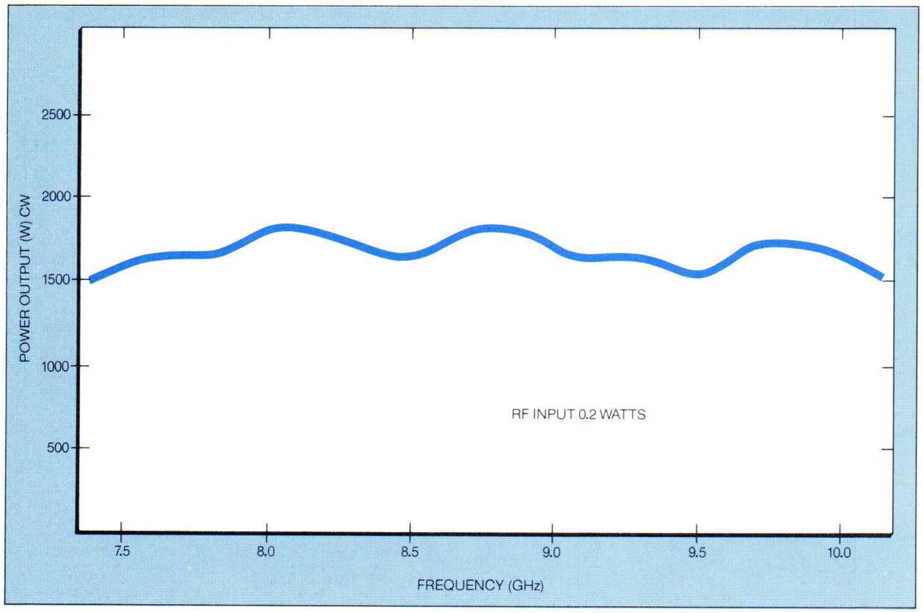

Figure 46 — *Power output with constant drive.*

Parallel pulsed TWTs

Figure 45 is a schematic of a technique to combine several conventional one kilowatt pulsed TWTs to attain higher pulsed power output over a broad bandwidth.

In such a combiner system, accurate phase tracking for all components over the frequency range is a critical requirement for satisfactory performance. The input dividers are 3 dB hybrids while the output combiners (hybrid or "magic T") have to be capable of handling higher peak and average power levels over large bandwidths.

Phase compensation is required for each tube pair to ensure the correct phase relationship in each combiner. Each of the tubes also requires an amplitude and phase equalizer so phase tracking can be kept within +20° over an octave bandwidth, provided that their grid and cathode voltages are also individually optimized.

With all these provisions, the combiner losses are still in the order of 1.5 dB over the band. Four tubes at the 2.5 kW level would, therefore, provide a combined peak output power of 7.0 kW.

In some applications, coupled-cavity TWTs are needed to provide the RF performance and several Hughes types have been utilized. One example is rated at 10 kilowatts peak, 2% duty over the band 7.5-10 GHz, and another provides over 1500 watts CW over the same bandwidth, as shown in Figure 46.

Continuous-wave TWTs

In addition to these pulsed types, high-power CW TWTs are used in broadband airborne jammer applications (see Figure 47). An integral solenoid provides a compact, rugged device for tactical environments.

Currently, development work is underway at Hughes on 200-watt CW tubes in the 2 to 18 GHz bands for ECM and ground terminal applications. Figure 48 and 49 illustrate typical performance characteristics of these devices.

A shift to CW radar

Recent changes in airborne tactics have shifted interest to the advantages of CW radar over the earlier pulsed techniques. Pulsed radars transmit short bursts of energy and then turn on the receiver between bursts. CW radar, however, uses antenna isolation and frequency resolution to detect the return signal.

The countermeasures to these radars are:

a) Deception jamming which uses transmitted signals so as to confuse the radar's data processing system.

b) Noise jamming which uses high-power density RF to obscure the radar return.

Each approach has strong advantages in varied tactical situations, but they are most effective when used together.

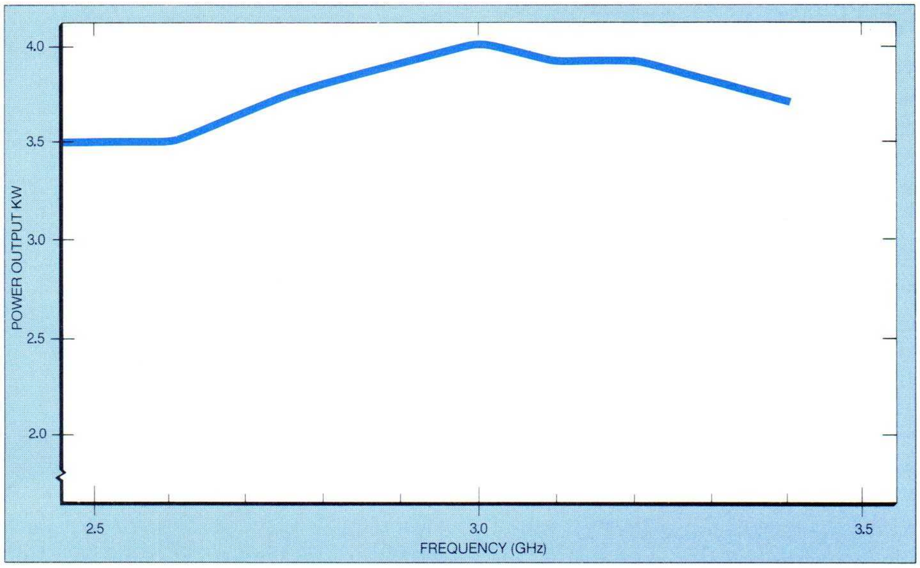

Figure 47 — *Output power with constant RF drive.*

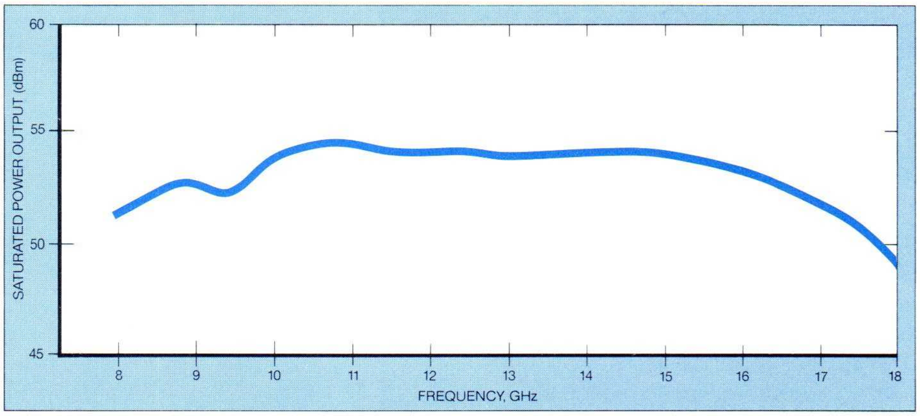

Figure 48 — *CW saturated power output.*

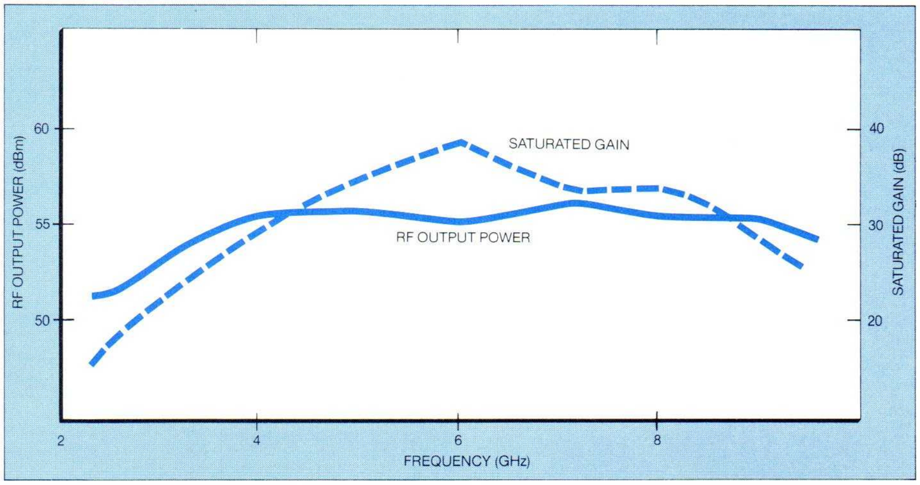

Figure 49 — *Saturated CW gain/power vs. frequency.*

One way to achieve this objective, shown in Figure 50, is to use two TWTs, operating in parallel from a single power supply. One is a pulsed TWT for deceptive schemes; the other, a high power CW TWT used for barrage jamming modes.

This approach is based on the available single-mode TWTs previously described, and recent improvements have been made in both pulsed and CW single-mode TWTs in regard to higher power output, extended bandwidth and improved duty cycle. For example, a recently developed I-J band-pulsed TWT, is rated at 8% duty cycle for performance as shown in Figure 51.

However, newer system concepts utilize a *single* multi-mode TWT to provide both the pulsed or CW output. This approach has obvious simplicity as well as inherent savings in size and weight.

Multi-mode TWTs

Key design features of these new multi-mode devices include a shadow gridded tetrode electron gun to provide the varied beam operating parameters. In addition, nondispersive circuit techniques are used to achieve wider bandwidths. Unique attenuators and velocity step tapering are also used to inhibit backward-wave oscillations and enhance tube stability. Integral barrel PPM-focusing provides excellent RF performance as well as a reliable rugged device which meets the stringent requirements of modern airborne environments.

Figure 52 shows typical performance for a multi-mode TWT. Flexibility in providing for intermediate modes allows the designer to adapt the system to a wide range of output power requirements. Specific applications for such multi-mode performance should be discussed with Hughes at the time of system design to benefit from the latest developments in this area.

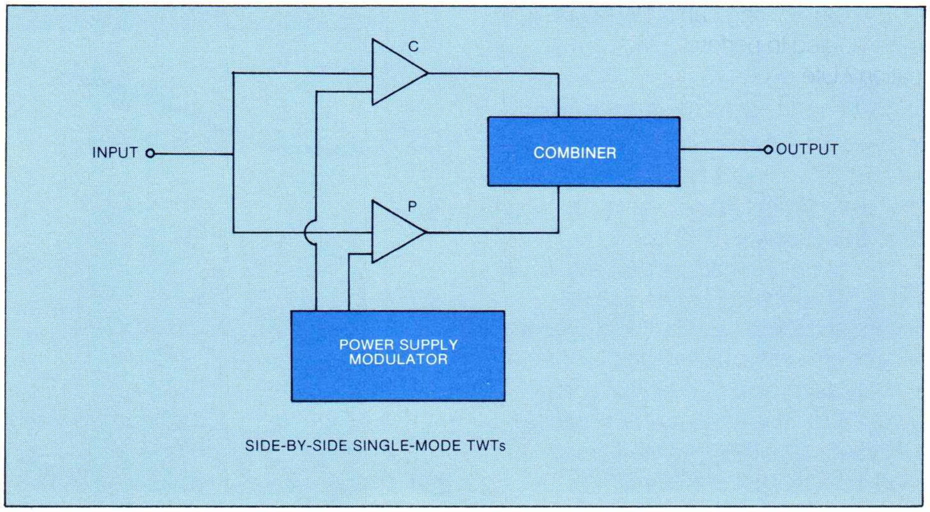

Figure 50 — *Two TWTs are operated in parallel from a single power supply, one pulsed TWT for deceptive schemes and the other as a high-power CW TWT for jamming.*

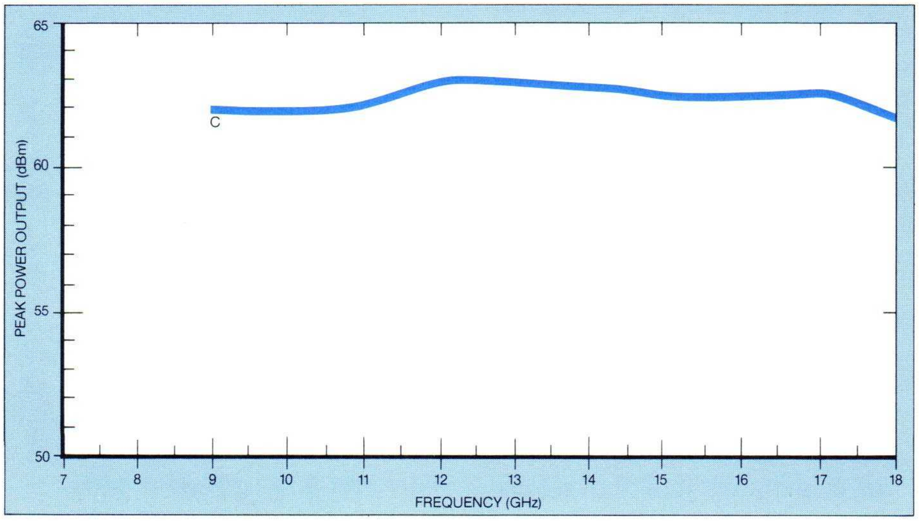

Figure 51 — *Power Output vs. Frequency at 8% duty factor.*

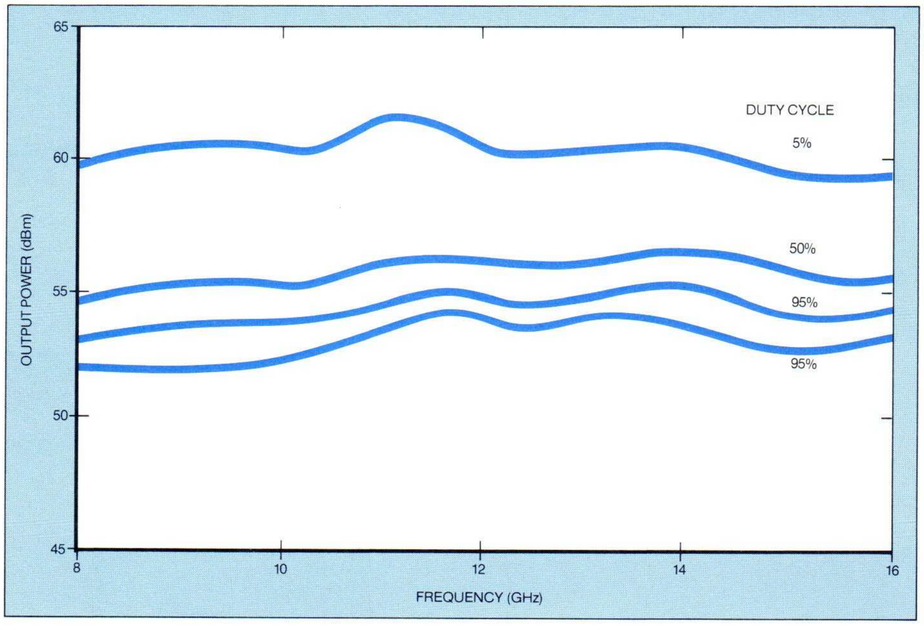

Figure 52 — *Multi-mode performance of a Hughes' multi-mode TWT offers the systems designer flexibility in output power requirements.*

The TWT in Space

Just how long can a TWT/TWTA be expected to perform in a space application? Life experience indicates that 10 years is a reasonable estimate for the life of Hughes space hardware.

Shown in Figure 53 are typical TWTAs for space communications. These highly sophisticated microwave amplifiers provide the necessary high gain required for downlink transmission. This high gain is attainable due to the combined high conversion efficiency of the TWT and the electronic power conditioner (EPC).

Hughes space experience began in 1963 with the launch of the Syncom Satellite series. These Hughes/NASA satellites were the first attempt at placing satellites in synchronous orbit. Syncom also contained the first of a continuing line of space TWTs, with an in-orbit operating time approaching 20,000,000 hours. This is in addition to the life test experience of nearly 5,000,000 hours. The in-orbit TWT experience has been accumulated on over 35 major space programs, including Apollo, Mariner, Surveyor, Pioneer, Intelsat series, Skylab, Westar, Marisat, TDRSS, DSCS-II and DSCS-III.

In the case of TWTAs, Hughes experience began in the mid-60's with the Lunar Orbiter program. Since that time, TWTAs have been developed and delivered for military, NASA, commercial and international space applications. The RF-power capabilities of such units range from 200 mW to 100 W of CW operation. Hughes has on-going programs to investigate higher efficiency, lower weight, smaller size, higher reliability, the interface problems between TWT and the EPC, and the interface between the TWTA and the spacecraft.

The space TWT

The design philosophy adopted for the TWT during the Syncom era provided hardware that was rugged, reliable, lightweight, and with a long service life. The same philosophy has carried over in the more recent programs to achieve the same desirable features for the EPC. While maintaining the original design philosophy, Hughes has developed and implemented the most up-to-date state-of-the-art technology in the areas of metal-ceramics processing and mechanical and electrical design techniques. This combination of philosophy and technology has produced hardware that has consistently proven itself to be fully space-qualified.

Keys to a long-life TWT

The life determining design feature of a TWTA is the cathode of the tube. Hughes, in the late 1950's, selected oxide cathodes as the source of thermionic electron emission for stable, long-life performance. In the years since, this has proven to have been an excellent selection, having been confirmed by life test as well as actual operation in the deep space environment.

To assure long life with an oxide cathode, the current emission density or loading of the cathode is usually kept below 250 Ma/cm^2.

There are three life-limiting mechanisms for an oxide-coated cathode: the

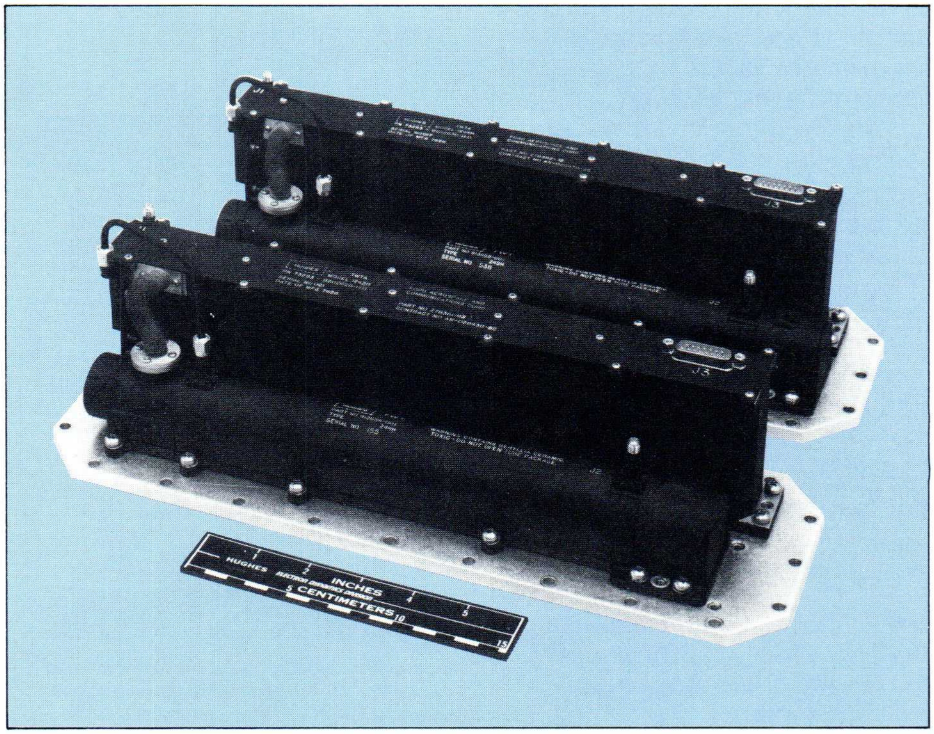

Figure 53 — *C-band 4.5 W and 8.5 W TWTAs.*

total coating depleted, the change of mixed oxide coating stoichiometry, and the activator arrival rate. All of these mechanisms change with operational time depending on temperatures, structural dimensions, initial concentrations of activators and coatings, and the vacuum environment within the TWT.

From accumulated life data, the temperature, minimum activator arrival rate, allowed coating depletion, and the limited oxide mix stoichiometry are empirically determined. The dimensions, concentrations of activators and coatings, and the vacuum environment are controlled by well-proven processes and procedures.

Electron gun optics are selected for conservative space charge, limited emission density, and cathode temperature at a perveance, voltage, and beam size appropriate to the tube design.

In addition to the oxide cathodes used for space qualified TWTs, the so-called dispenser cathode is gaining some acceptance. The dispenser cathode lends itself to higher loading values permitting a lower area convergence in the design of electron beams for use at the higher frequencies. Thousands of hours of life testing have been completed and this testing continues to investigate and establish the dispenser cathode as a long-life element, at least equal to the well-proven oxide cathode.

Other factors which must be taken into account to insure long life are the heater which heats the cathode, the metal-ceramic seals which must maintain a near-perfect vacuum, and the focusing structure which must assure maximum beam transmission.

Cathode-knee temperature

An idealized curve of cathode current versus cathode temperature is shown in Figure 54. The region to the left of the knee is known as the temperature-limited-emission region. The region to the right, the area where tubes are normally operated, is the space-charge-limited-emission region. Typically, in long-life TWTs, some finite margin should exist between operating temperature and knee temperature.

Another characteristic of long-life TWTs is that the cathode-knee temperature is relatively low and is stable as a function of time after initial processing. A method for measuring this parameter, known as cathode activity test, is to monitor the cathode current as a function of time after removal of heater voltage — while maintaining all other voltages applied to the tube.

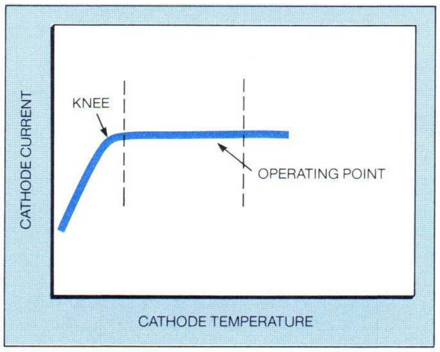

Figure 54 — *The region to the left of the knee is the temperature-limited-emission region, to the right is the space-charge-limited-emission region.*

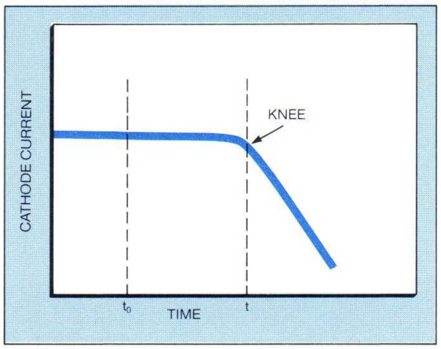

Figure 55 — *A cathode activity test is used to assure that the cathode-knee temperature is relatively low and stable after initial processing.*

The time-to-knee in Figure 55 is directly related to the knee temperature through the thermal properties of the overall cathode structure. This curve is taken periodically during the TWT and TWTA burn-in period to assess the quality of the cathode. The time-to-knee must be stable during final burn-in hours to assure a long-life device.

Long-life heaters

The heater, which is the hottest element in the TWT, must provide the necessary energy to maintain the correct cathode temperature. For this reason the selection of reliable high-temperature materials and the limiting of the maximum heater temperature through optimum thermal design are necessary factors in obtaining a reliable, long-life heater design.

It should also be noted that during turn-on and turn-off cycles, the heater must go through a change in mechanical dimensions. The design must provide for this expansion and contraction without over-stressing the heater wire or the heater coating which has been applied as an insulator.

The vacuum envelope

The required vacuum environment for the cathode can be degraded in several ways, all of which tend to increase the pressure and impair cathode operation. Among these are a leak in the vacuum envelope, internal outgassing due to overheating, or arcing with attendant poisoning and/or ion bombardment of the cathode.

The incidence of vacuum envelope leaks is kept extremely low by the use of good design, proven reliable metal-ceramic joining techniques, and very high quality materials.

Careful analysis, together with thorough thermal design and testing, leads to conservatively low operating temperatures within the TWT. Under these circumstances, the TWT bakeout temperature is never approached (except at the cathode) in normal specified tube operation. Hence, the cleaning and outgassing function of bakeout is not sacrificed. A heated getter provides internal pumping capacity over extended life.

Screening and storage tests are performed during the manufacturing cycle to eliminate any possible leaks.

Beam focusing

Space TWTs make exclusive use of PPM focusing. There are three types of material which are used: platinum-cobalt, Alnico-8, and more recently, samarium-cobalt. These materials have been chosen so that a maximum magnetic field may be achieved. During testing, the magnetic field may be altered slightly by placing small magnetic shunts on the outside diameter of the magnet stack.

Critical design parameters

The primary design parameters which differ according to the different applications are frequency, power level, gain, bandwidth and life. Secondary considerations which must be taken into account to achieve the best tradeoffs for a specific application are efficiency, linearity, size and weight.

TWT size is determined by the physical laws which determine the frequency response, linearity, and efficiency. The weight depends on the size, materials used, and the structural techniques employed for the necessary strength to survive the thermal stresses, pyrotechnic shock and vibrations encountered during launch and operations.

The space EPC

Hughes has developed and manufactured EPCs for TWTs capable of 200 mW to 100 W of CW RF power. These units are designed to supply cathode voltages from 1.2 to 5 kV and will operate from a regulated or unregulated bus. In addition, EPCs have been developed for pulsed applications with cathode voltages in excess of 10 kV.

The EPC converts the regulated or unregulated spacecraft bus voltage to dc voltages at the proper levels and with the necessary regulation to operate a given TWT. A simplified block diagram of a typical EPC is shown in Figure 56.

The heart of the EPC is a new approach to voltage conversion and regulation known as the "Venable Converter," patented by Hughes. The converter utilizes a circuit configuration that achieves such desirable features as higher efficiency, a single circuit for regulation and conversion, minimized output filter requirements, and simplified control system applications.

The size and weight of the EPC is dependent on the thermal interface, RFI and telemetry requirements, spacecraft power bus, allowable ripple current that the TWTA can inject on the power bus, residual AM and PM noise, and shock and vibration levels to be experienced in the launch environment.

Hughes has on-going programs exploring efficiency improvements, longer life and reliability, packaging techniques, the effects of radiation, multi-stage collector operation, and system interface as it relates to both thermal factors and the power bus of the spacecraft.

Future trends

The future trends being dictated by systems requirements are toward higher frequency, greater efficiency, increased reliability, longer life, smaller size, lighter weight and, in some cases, higher power.

The migration to higher frequency, from the standpoint of the TWT, will result in smaller and lighter weight devices. However, as the frequency increases, cathode voltages usually increase, causing the EPC to grow in both size and weight. This, in turn, will force the investigation, qualification, and in some instances, development of new materials and processes.

Future improvements in efficiency will be gradual as the TWT and EPC approach maturity. Efforts will be continuing in resynchronization and multi-stage collector techniques for TWT efficiency improvements, while new circuit techniques will be explored and new components evaluated for efficiency improvements in the EPC.

Higher reliability can be achieved by additional screening, testing and burn-in. This is usually a trade-off of time and cost. Longer life may be brought about by lower cathode loading, incorporating into future designs the experience gained through life testing and actual system usage, and a continuous program of cathode material improvement and evaluation.

The smaller size and lighter weight will come about by exploring and developing new materials, more efficient ways to package the EPC, improved techniques of heat removal, and working in close relationship with system engineering so that a given TWT/TWTA is designed for optimum performance in a package that meets the environmental and mechanical interface requirements.

Higher power TWTs/TWTAs have been developed and manufactured for other applications. Therefore, it will require the transfer of that technology to space-qualified hardware, while still maintaining and assuring the stringent requirements needed for such hardware.

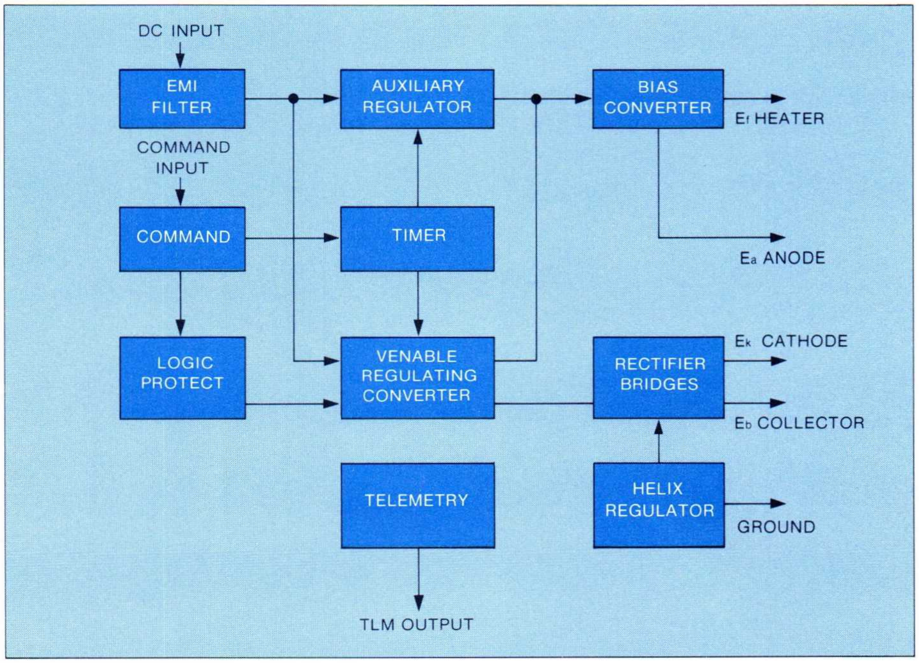

Figure 56 — *The heart of the EPC is the new approach to voltage conversion and regulation known as the "Venable Converter."*

Earth Terminal Communications

TWTs, TWTAs, and HPAs (high-power amplifiers) used in transmitter subsystems for satellite earth stations require special performance characteristics if they are to meet the demanding requirements of satellite up-links.

The stable and controllable devices must provide low distortion operation for applications such as video, single channel per carrier, TDMA, FDM, and other up-link carriers.

Each type of carrier or service places its own special requirement on RF performance in the areas of gain variation, group delay, AM/PM intermodulation distortions, and residual modulation.

In addition to RF performance, the communication power amplifier must offer high reliability to insure minimum down time and loss of traffic revenue. When an amplifier is down it must be supported by a combination of redundant back-ups, spares, documentation, factory support, and a low MTTR (Mean-Time-To-Repair).

Consideration must also be given to the amplifier's ability to interface properly with other operational and control subsystems in the earth station. Interfaces may be limited to RF and prime power in a small remote terminal, or they may include complete monitor, alarm, and control functions in a major earth station. Control of the HPA subsystem may be via a local control panel, or via satellite from a distant earth station.

From TWTs to complete subsystems

Hughes Electron Dynamics Division offers a wide range of low-, medium-, and high-power amplifiers and subsystems meeting the most demanding reliability, performance, and control requirements for satellite earth station transmitters.

The company's current products cover C-, X-, and Ku-bands, and range from a basic TWT and power supply configuration to a complex sub-system offering redundancy and RF power combining. Current development programs within Hughes will provide a basis for future HPA products in the 30-GHz-and-above up-link bands.

Figure 57 shows the basic functional blocks of a power amplifier incorporated into a redundant subsystem. Hughes amplifiers and subsystems use helix and coupled-cavity TWTs, together with solid-state power supplies and high quality microwave components. Reliability and maintainability are the keys to success. Data sheets showing operating characteristics are available for each of the HPA products offered.

Low-power amplifiers

The Hughes 9000H series of low-power amplifiers is configured for use as intermediate amplifiers in large satellite earth terminals and as output amplifiers in small or remote terminals. Figure 58 shows a Model 9040H02 power amplifier currently being used in a large number of remotely located, unattended bush-type terminals.

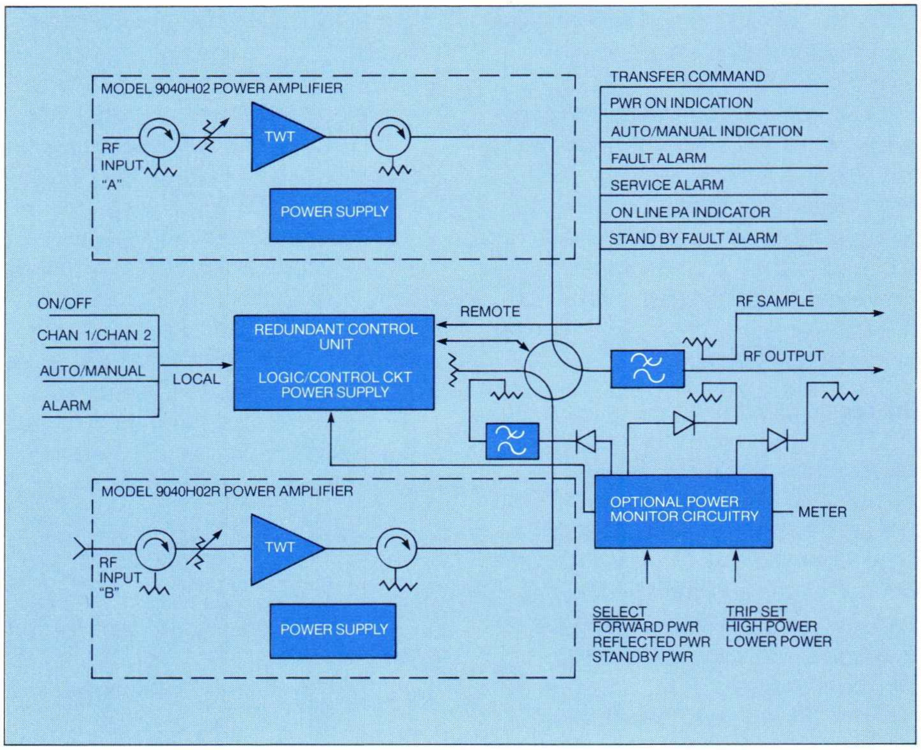

Figure 57 — *A typical redundant HPA subsystem block diagram shows automatic and remote control features and configuration.*

Each unit is completely self-contained and consists of a PPM-focused TWT, solid-state power supply, integral cooling and protective circuitry. Optional RF features include a solid-state driver for increased gain, output isolator for TWT protection, band-pass filter, input isolator, and input adjustable attenuator. The series uses any of several rugged metal-ceramic TWTs derived from Hughes' space-qualified devices to provide 10 to 50 watts of RF power output in the 6, 8, and 14 GHz satellite up-link bands.

The solid-state power supply offers optimum interface with the TWT for proven reliability and tube protection. Power consumption is held to a minimum. Protective features include excess helix current overload, thermal overload and automatic time delay for tube warm-up. Other available features associated with the power supply are high-voltage interlocks, operation from 115 Vac, 230 Vac, 48 Vdc or 24 Vdc input power, remote controls/status indicators for remote operation, and redundant power amplifier operation.

The compact, lightweight series 9000H units are particularly suited for transportation to remote sites. They can be mounted in a 19-inch rack with a panel height of 3½ inches and a maximum depth of 20 inches, and are available in a basic configuration (including a power supply, TWT, and control/protection circuitry) or as a complete power amplifier including optional features. In addition, an expanded subsystem, shown in Figure 59, is availble for redundant operation of any two amplifiers in the 9000H series.

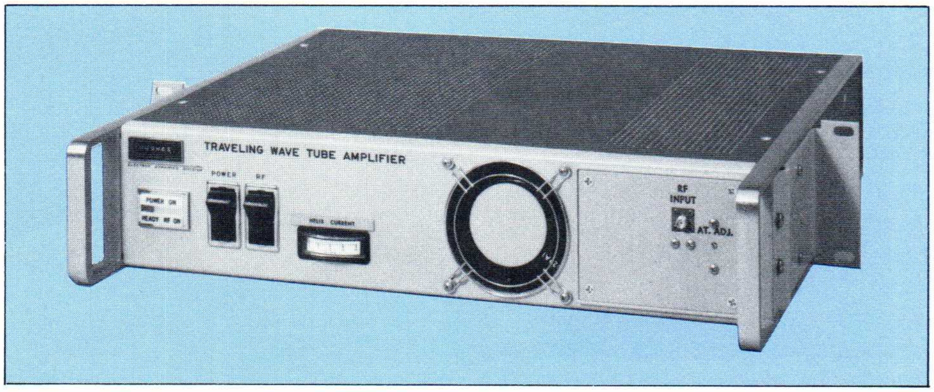

Figure 58 — *The compact Model 9040H02 amplifier is the workhorse of small bush-type earth terminals. It offers 40 watts at 6 GHz and a MTBF greater than 50,000 hours based on actual field experience.*

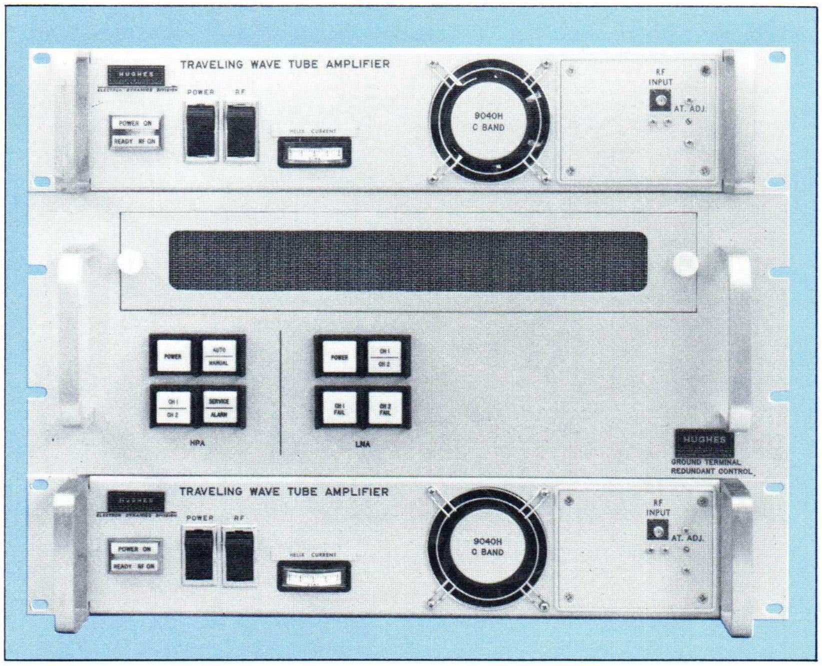

Figure 59 — *Two low-power amplifiers combined with a redundant control unit provide 40 watts at 6 GHz in the Model 9640H02 redundant subsystems.*

Figure 60 — *Hughes 9200H series of high-power amplifiers.*

High-power amplifiers

The Hughes 9200H series offers higher output power than the 9000H series along with a larger number of control interfaces and self-protect features. Figure 60 shows a typical HPA. The unit provides 400 watts at 6 GHz or 250 watts at 14 GHz, using the same power supply and package design. As seen in Figure 61, the high-power amplifier provides, as required, a high degree of control and protection. The series uses air-cooled and either PPM-focused helix or coupled-cavity TWTs.

The 9200H series is available as single HPAs or in redundant or power combined subsystems as shown in Figures 62 and 63. Subsystems include the logic and RF switches required for automatic and manual selection of the on-line amplifier(s). Completely integrated subsystems provide local or remote control and interfaces, making them ready to "drop-in" into almost ay type of satellite earth station.

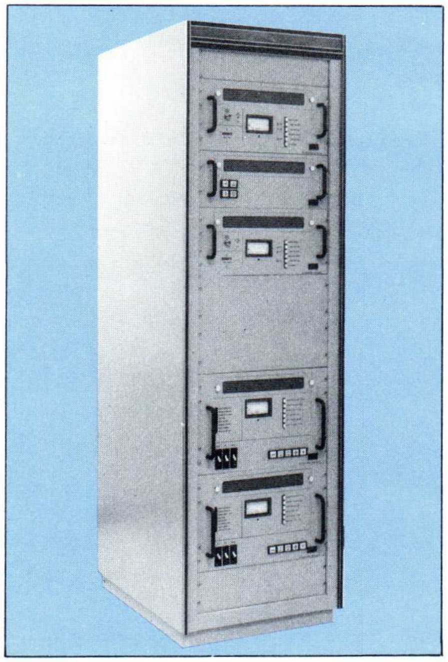

Figure 62 — *The Model 9740H02 redundant HPA subsystem includes two (2) high-power amplifiers and a redundant control unit in an integrated cabinet. 350 watts at 6 GHz is automatically provided from the on-line unit or the standby unit in the event of a fault.*

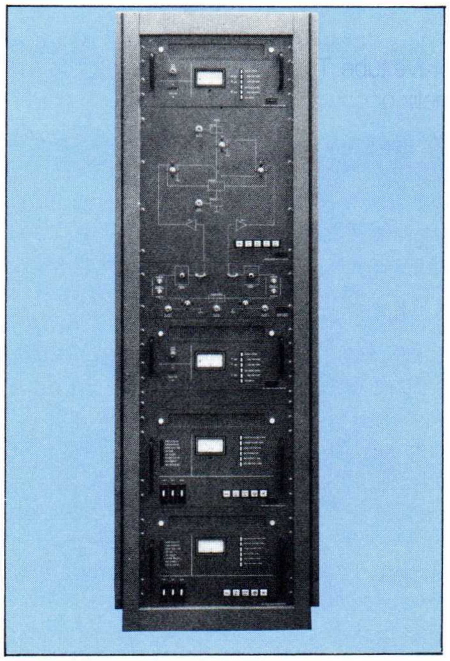

Figure 63 — *High-power amplifier subsystem features redundant or power combined operations in manual or automatic modes to provide 350 or 700 watts at 6 GHz. Input (upconverter) switching and mimic panels are also featured.*

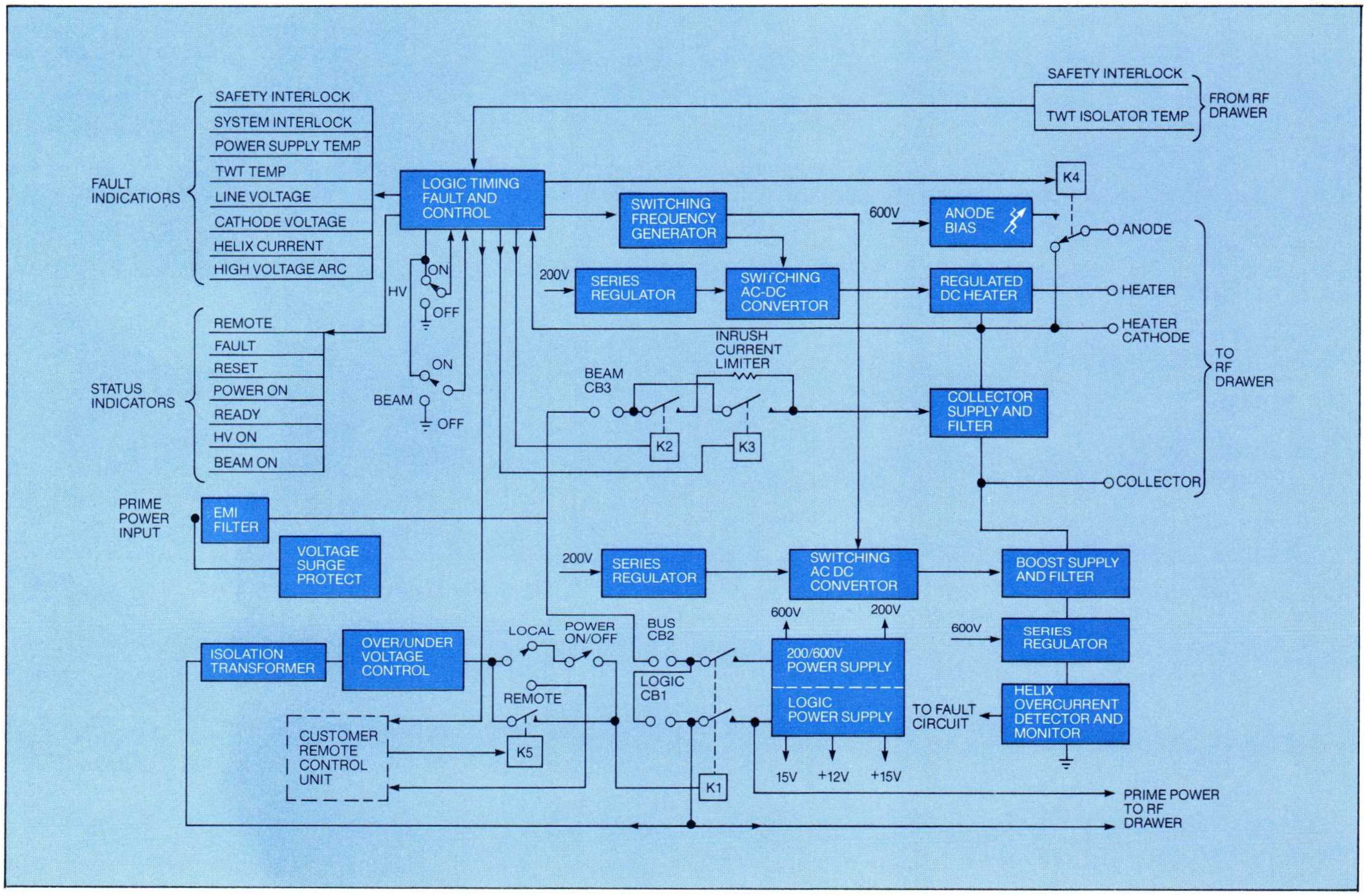

Figure 61 — *Electronic power conditioner (EPC) simplified block diagram.*

Communication TWTs

The heart of any HPA is the microwave tube. The Hughes HPAs employ helix or coupled-cavity TWTs designed to meet the low distortion requirements of satellite earth station transmitters.

The type of TWT used will depend on the application and power frequency tradeoffs. For example, a helix TWT at 14 GHz can be used to provide 250 to 300 watts of RF power while meeting life and reliability requirements. Above this power level, conservative design requires the use of a higher power, coupled-cavity TWT.

Two helix-type TWTs are shown in Figure 64. Both the Model 662H and Model 881H are metal-ceramic tubes requiring forced air cooling. Electronic requirements for both tubes are nearly identical and can be operated from power supplies of the same design.

Figure 65 shows the typical flat gain-versus-frequency response of Hughes communication TWTs.

The TWTs offer a low-profile package with heat deflectors for horizontal or vertical air flow (input and output). A threaded insert is provided at the tube collector for a thermal sensor.

Hughes also offers a number of communication TWTs of the coupled-cavity type. A typical TWT used in the Model 9260H04 HPA is shown in Figure 66.

Minimized gain and phase variations

Typical of these TWTs is the Model 792H which was developed for use as the final power amplifier in the FSC-78 military satellite communications ground stations. It operates over the 7.90 to 8.40 GHz frequency range, producing up to 5 kW of RF output power. For such communication systems, low distortion is required at all output power levels since the overall system performance is, in large part, determined by the output TWTs performance. Extremely low amplitude and phase ripple is achieved by means of special tube construction techniques and an integral gain equalizer.

Other tubes designed for these applications include the 8760H which provides up to 1.2 kW of CW power in the 7.9 to 8.4 GHz band and the 876H providing 600 to 700 W of CW power at 14.0 to 14.5 GHz. Both tubes are PPM-focused and air cooled. In the area of higher power tubes, the 870H provides 5 kW of CW power in the 14.0 to 14.5 GHz band and the 8723H provides 14 kW in the 7.9 to 8.4 GHz band.

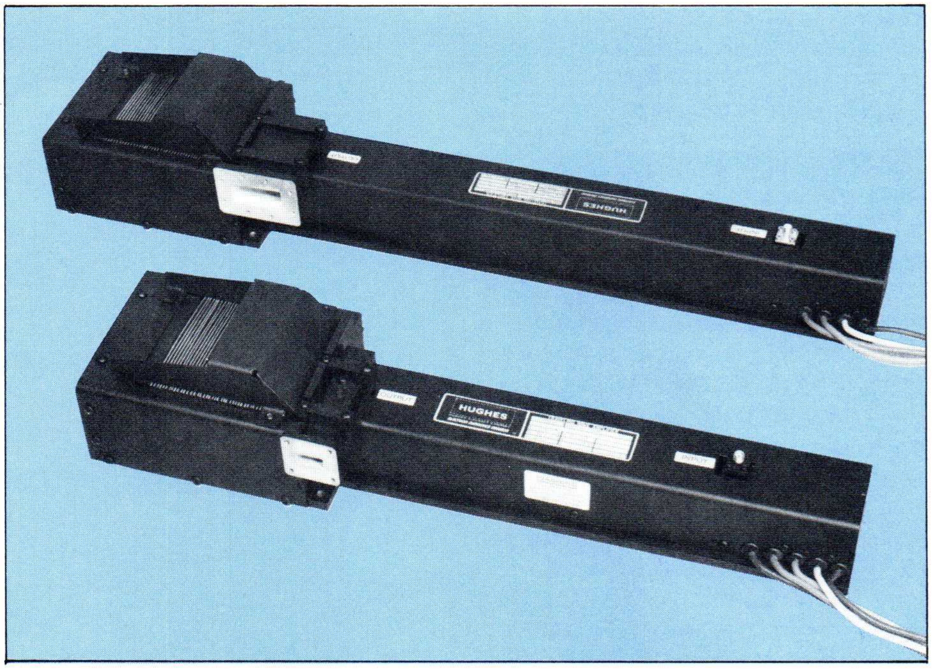

Figure 64 — *Models 662H & 881H 250 and 400 watt helix traveling-wave tubes used in commercial earth terminals at 6 and 14 GHz. Both are PPM-focused, air-cooled, and compatible with a single power supply design.*

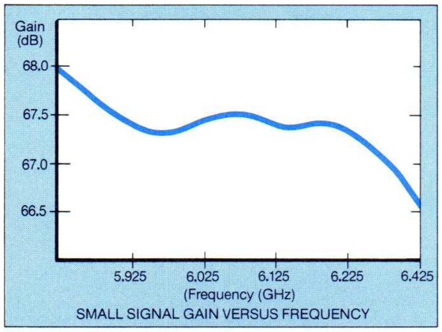

Figure 65 — *Typical small signal gain vs. frequency for Model 662H TWT 400 watts—6 GHz.*

Both tubes are solenoid-focused and liquid-cooled.

Special emphasis on minimizing gain and phase variations is given in the design of the circuits for these tubes. Gain and phase variations result from feedback caused by mismatches in the circuit sections. The principal mismatches occur at the ends of the sections; i.e., the internal terminations and the input and output RF waveguide couplers. The larger the mismatches at these points and the higher the gain in each circuit section, the greater the gain and phase variations.

The internal terminations normally used in coupled-cavity circuits are of relatively short electrical length, being confined to a single cavity. As a result, the mismatch of these terminations can be reduced to a low but imperfect level.

Hughes has developed and patented a tapered internal termination for coupled-cavity circuits that extends over several cavities. The long electrical length of this termination and the gradually tapering loss pattern results in a very low mismatch. This technique also introduces in-band loss to the section, further reducing the feedback effect.

The tapered loss is achieved by using small cavities adjacent to the circuit cavity. These cavities are loaded with lossy ceramic "buttons" that protrude significantly into the cavity. The protrusion, or re-entrancy of a button determines the amount of in-band loss; the amount of loss is easily tapered in successive cavities by simply changing the amount of button re-entrancy, as illustrated in Figure 67.

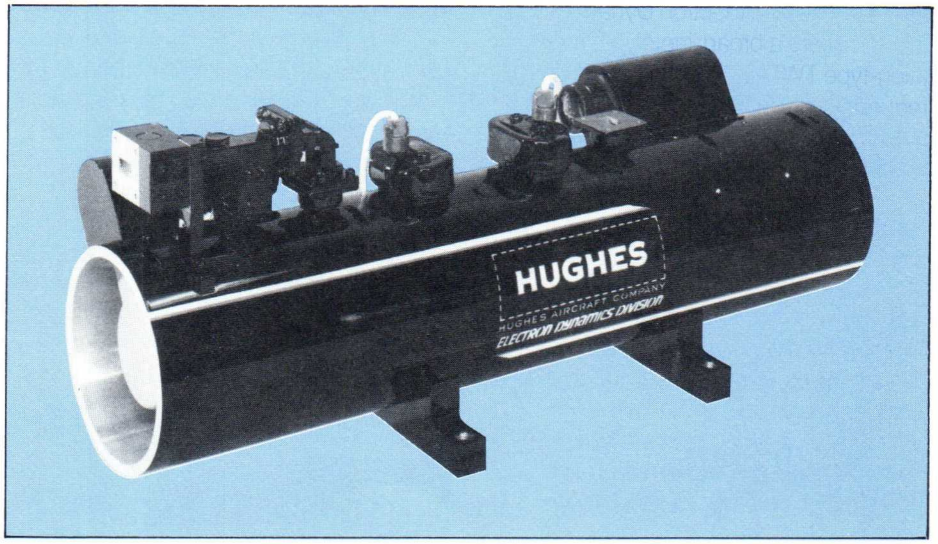

Figure 66 — *Hughes Model 876H coupled-cavity communications TWT provides over 700 watts at 14.0-14.5 GHz.*

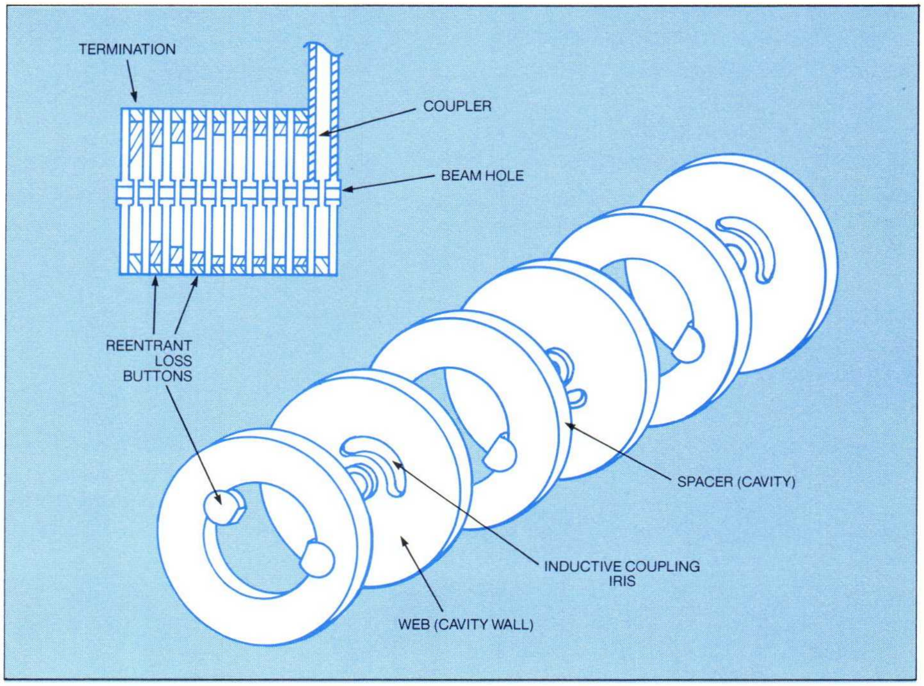

Figure 67 — *In the Hughes patented coupled-cavity slow-wave circuit, lossy ceramic buttons are used to produce a gradually tapering loss pattern to reduce mismatch between internal terminations and the input and output RF waveguide couplers.*

Instrumentation TWTAs

The Hughes Electron Dynamics Division offers a broad line of instrumentation-type TWTAs. The units cover the frequency range of 1 to 18 GHz, with a power output of 10 or 20 watts, in all standard frequency bands, multi-bands, and extended frequency bands. In addition, 1-watt units are offered in the 18 to 40 GHz range.

The Hughes Instrumentation Power Amplifiers are widely used in ECM, missile and radar checkout equipment, TV links, test equipment, radar ranges, satellite simulation, communication links, driver units, medical research and many other applications that require amplification of an RF signal.

Long-service life

Off-shoots of the long-life, highly reliable TWTs developed by Hughes for space applications, and provided with completely solid-state power supplies, the Instrumentation Power Amplifiers warranted for one full year — regardless of the operating hours.

The amplifiers are packaged in a lightweight, small-size enclosure (Figure 68) which includes a self-contained cooling system, automatic time delay, helix current overload, thermal overload and RF output connector interlock. The power supply provides a dc heater voltage and a highly regulated helix voltage to assure a high degree of gain stability.

The units are offered with a wide range of options so that they may be used in a variety of applications, and may be readily adapted to a specific requirement without major modifications.

Off-the-shelf delivery

Hughes has built the Instrumentation Power Amplifier on a production basis since 1969, and can supply most bands and power levels on an "off-the-shelf" basis. The units are also offered on the Government's General Services Administration (GSA) Authorized Federal Supply Schedule. All units are shipped with an Operation and Maintenance Manual which includes schematic and parts list. Hughes also maintains spare parts and the necessary facilities to service and calibrate the units in a timely manner.

Figure 68 — *Instrumentation TWTA.*

Looking Ahead

The TWT is now a mature device, being developed and manufactured by a mature industry, geared to the hard economics of the marketplace. There is, therefore, no reason to look forward to dramatic breakthroughs in the major characteristics of the TWT device.

There *will be,* however, a steady and significant improvement in its reliability, adaptability, and cost. Moreover, it would only be fair to state that the ultimate capabilities of the TWT in terms of bandwidth, power output, efficiency, size, and signal fidelity have not yet been fully exploited by present-day systems. Only in a few select areas, such as communication satellites, have TWTs been employed to the maximum of their intrinsic capabilities.

This situation will undoubtedly change as the systems of the future are pushed toward better performance — without corresponding increases in size or complexity. Even though new classes of TWTs are not likely to appear in the foreseeable future, the current effort to improve efficiency and power-handling capability will cause a measure of excitement in the industry. The mix of devices will also change, as advanced systems replace some of the more obsolete equipment. Those who are in the TWT manufacturing industry cannot expect to maintain their current level of business unless they pursue a vigorous development program to upgrade their devices. In spite of phased arrays, for example, the TWT will remain a rather sophisticated custom-built device, with most of the output of the industry going into complex military systems.

At the lower power levels, there will be ever increasing competition from solid-state devices. And with the introduction of rare-earth magnetic materials, such as samarium-cobalt, PPM focusing will take over a major part of the low-to-modest power levels, with solenoid focusing employed only in those cases where it is mandatory, such as a 10-kW CW X-band transmitter TWT.

More emphasis will be given to making TWTs more adaptable to the modern airborne environment, which requires compactness and high operating temperatures. Heat pipes with vapor-phase cooling will become increasingly important as a highly efficient method for transferring large amounts of heat in a very confined space.

Life and reliability will also be given a great deal more attention in the future. Today, the TWT is less than adequate in these two categoris, but not because of fundamental limitations. Like any other parameter, reliability costs money and development time. The more reliability, the more the cost. However, in terms of total system cost and life-cycle cost, the net savings may be quite dramatic. The real advances in this area will come as a result of conservative and skillful designs, not as a consequence of legislation and specification writing.

A Spectrum of TWTs and TWTAs

Table A—PULSED RADAR and ECM TWTs

	Model Number	Frequency Range (GHz)	Power Output (kW)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current Ik (A)	Dimensions L x W x H (Inches)
S-Band	555H	2.0-4.0	1.25	0.10	33	-7.8	1.8	17.5 x 2.5 dia
	658H	2.5-8.0	1.0	0.10	30	-10.0	2.5	19.0 x 3.63 x 2.56
	589H	2.7-3.1	125.0	0.025	50	-45.0	17.0	58.0 x 6.0 dia
	584H	2.8-3.0	300.0	0.022	21	-57.0	28.0	41.0 x 6.0 dia
	588H	2.9-3.2	125.0	0.08	50	-45.0	17.0	57.0 x 6.0 dia
	587H	2.9-3.1	125.0	0.05	50	-45.0	17.0	56.0 x 6.0 dia
	▲560H	3.1-3.3	250.0	0.02	53	-53.0	21.0	54.0 x 6.0 dia
	8503H	3.1-3.5	120.0	0.08	50	-42.0	17.0	43.5 x 10.0 dia
	559H	3.1-3.5	125.0	0.08	50	-42.0	17.0	52.0 x 6.0 dia
	▲598H	3.1-3.6	250.0	0.10	50	-52.5	24.0	48.0 x 6.0 dia
	595H	3.4-3.7	220.0	0.03	21	-51.5	23.0	33.0 x 14.5 x 9.5
C-Band	639H	4.0-8.0	1.0	0.02	30	-10.0	2.5	14.5 x 2.75 dia
	641H	4.0-8.0	1.25	0.1	30	-9.75	1.8	14.5 x 2.75 dia
	▲580H	4.0-8.0*	1.0 p/0.1 CW	0.05	40-23	-9.5	1.2/0.300	20.0 x 4.0 x 3.2
	657H	5.3-5.7	65.0	0.04	47	-37.0	11.0	35.5 x 6.7 x 8.7
	621H	5.4-5.7	50.0	0.025	50	-35.0	8.0	29.0 x 3.3 x 7.5
	622H	5.4-5.8	75.0	0.025	50	-38.0	11.0	29.0 x 3.3 x 7.5
	635H	5.4-5.8	165.0	0.035	47	-48.5	17.0	34.5 x 12.0 dia
	676H	5.4-5.9	12.0	0.03	45	-23.0	4.0	27.0 x 8.75 x 8.0
X-Band	738H	7.5-10.0	10.0	0.01	40	-32.0	7.0	26.0 x 5.5 dia
	788H	7.5-10.0	10.0	0.02	40	-33.0	7.0	26.0 x 5.5 dia
	▲869H	8.0-16.0*	1.0 p/0.1 CW	0.05	40/20	-11.0	1.2/0.300	17.0 x 4.0 x 3.2
	774H	8.0-16.0	1.25	0.04	50	-11.0	2.1	14.0 x 2.5 x 2.0
	8722H	8.0-18.0	1.0	0.04	40	-11.5	2.1	16.0 x 2.5 x 2.0
	307H	8.6-9.5	50.0	0.01	50	-36.0	10.3	21.0 x 5.0 dia
	725H	8.5-9.6	1.58	0.04	40	-11.0	1.5	17.0 x 4.5 x 5.0
	8753H	8.5-9.6	150.0	.035	53	-50.0	17.0	31.0 x 7.5 dia
	308H	8.6-9.5	20.0	0.01	46	-24.0	6.0	19.0 x 4.0 dia
	8718H	8.6-9.4	35.0	0.012	52	-30.0	7.8	20.0 x 4.5 dia
	751H	8.8-9.7	50.0	0.01	52	-32.0	7.6	20.5 x 5.5 dia
	760H	8.9-9.9	40.0	0.01	42	-30.0	8.0	16.5 x 5.5 dia
	797H	9.0-9.8	9.0	0.5	54	-18.0	2.5	21.0 x 6.0 x 8.0
	750H	9.0-10.0	25.0	0.01	47	-24.0	5.5	18.5 x 5.0 dia
	8716H	9.0-9.2	120.0	0.0025	50	-43.0	13.5	24.0 x 5.0 dia
	796H	9.2-9.9	40.0	0.04	54	-32.0	7.0	20.5 x 5.5 dia
	▲8754H	9.0-18.0	1.5	0.08	45	-11.0	1.6	16.0 x 2.75 x 3.0
	8709H	9.2-9.4	26.0	0.012	47	-25.0	6.0	20.5 x 5.0 dia
	8715H	9.2-10.0	50.0	0.04	56	-32.5	8.0	24.0 x 5.5 dia
	8740H	9.3-9.9	50.0	0.02	50	-33.0	8.0	24.0 x 5.5 dia
	786H	9.3-9.9	50.0	0.07	47	-33.5	8.5	21.0 x 6.5 dia
	8708H	9.4-10.0	26.0	0.012	47	-26.0	6.0	21.0 x 5.0 dia
	719H	9.4-9.6	40.0	0.005	45	-26.0	6.8	15.0 x 3.8 dia
	781H	9.55-9.85	2.5	0.5	53	-12.0	1.2	16.0 x 6.0 x 7.5
	790H	9.6-9.8	1.0	0.20	50	-10.2	0.8	16.0 x 4.0 dia
	8725H	9.7-9.9	15.0	0.02	58	-23.0	4.0	18.0 x 3.3 dia
	8741H	10.0-10.3	4.0	0.20	33	-20.5	0.7	17.0 x 4.5 dia
	867H	11.0-17.0	5.0	0.02	40	-33.0	2.5	20.0 x 4.0 dia
Ku-Band	839H	15.0-16.5	100.0	0.005	50	-62.0	7.8	18.0 x 4.25 dia
	866H	15.7-17.7	10.0	0.5	33	-30.0	3.4	30.0 x 7.0 dia
	605H	16.0-16.5	100.0	0.005	40	-62.0	8.0	19.0 x 5.0 x 6.0
	854H	16.0-16.5	100.0	0.03	53	-65.0	8.1	20.0 x 6.0 dia
	838H	16.0-16.5	100.0	0.005	53	-63.0	7.7	16.0 x 4.0 dia
	835H	16.0-16.5	200.0	0.01	60	-85.0	13.0	27.0 x 6.0 dia
	820H	16.0-17.0	5.0	0.01	36	-24.0	1.5	14.0 x 3.5 dia
	830H	16.2-16.7	3.0	0.04	37	-22.0	1.3	16.0 x 4.5 dia
	861H	16.0-17.0	12.0	0.025	45	-30.0	2.0	14.0 x 4.0 dia
mm-wave	▲982H	93.0-95.0	0.1	0.5	50	-22.0	.088	18.0 x 4.0 dia

* = dual mode

▲ = under development

Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number	
44.45 x 6.35 dia	10.0	4.55	PPM	G	L	555H	**S-Band**
48.26 x 9.22 x 6.5	8.0	3.64	PPM	G	C	658H	
147.32 x 15.24 dia	205.0	93.18	PPM	SG	L	589H	
104.14 x 15.24 dia	185.0	84.09	PPM	SG	L	584H	
144.78 x 15.24 dia	200.0	90.9	PPM	SG	L	588H	
142.24 x 15.24 dia	195.0	88.64	PPM	SG	L	587H	
137.16 x 15.24 dia	180.0	81.82	PPM	SG	L	▲560H	
110.49 x 25.40 dia	190.0	86.18	SOL	SG	L	8503H	
132.08 x 15.24 dia	170.0	77.27	PPM	SG	L	559H	
121.92 x 15.24 dia	200.0	90.9	Sol	SG	L	▲598H	
84.0 x 37.0 x 24.0	100.0	46.0	PPM	SG	L	595H	
36.83 x 6.99 dia	10.0	4.55	PPM	G	FA	639H	**C-Band**
36.83 x 6.99 dia	10.0	4.55	PPM	G	L	641H	
50.8 x 10.16 x 8.13	10.0	4.55	PPM	SG	C	▲580H	
90.17 x 17.02 x 22.1	58.0	26.36	PPM	SG	L	657H	
73.66 x 8.38 x 19.05	40.0	18.18	PPM	SG	L	621H	
73.66 x 8.38 x 19.05	40.0	18.18	PPM	CP	L	622H	
87.63 x 30.48 dia	200.0	90.9	Sol	SG	L	635H	
68.4 x 22.23 x 20.32	55.0	24.97	PPM	SG	FA	676H	
66.04 x 13.97 dia	35.0	15.91	PPM	SG	L	738H	**X-Band**
66.04 x 13.97 dia	35.0	15.91	PPM	SG	L	788H	
43.18 x 10.16 x 8.13	10.0	4.55	PPM	SG	C	▲869H	
35.56 x 6.35 x 5.08	5.0	2.27	PPM	G	C	774H	
40.64 x 6.35 x 5.08	5.0	2.27	PPM	G	C	8722H	
53.34 x 12.7 dia	30.0	13.64	PPM	A	L	307H	
43.18 x 11.43 x 12.7	25.0	11.36	PPM	A	FA	725H	
79.0 x 19.0 dia	65.0	29.5	Sol	SG	L	8753H	
48.26 x 10.16 dia	21.0	9.55	PPM	SG	FA	308H	
50.8 x 11.43 dia	26.0	11.82	PPM	SG	FA	8718H	
52.07 x 13.97 dia	25.0	11.36	PPM	SG	L	751H	
41.91 x 13.97 dia	22.0	10.0	PPM	CP	L	760H	
53.34 x 15.24 x 20.32	45.0	20.45	IS	SG	L	797H	
46.99 x 12.7 dia	26.0	11.82	PPM	CP	FA	750H	
60.96 x 12.7 dia	35.0	15.91	PPM	CP	FA	8716H	
52.07 x 13.97 dia	28.0	12.73	PPM	SG	L	796H	
43.0 x 7.0 x 7.6	5.0	2.7	PPM	G	C	▲8754H	
52.07 x 12.7 dia	26.0	11.82	PPM	SG	FA	8709H	
60.96 x 13.97 dia	32.0	14.55	PPM	SG	L	8715H	
60.96 x 13.97 dia	32.0	14.55	PPM	SG	L	8740H	
53.34 x 16.51 dia	45.0	20.45	IS	SG	L	786H	
53.34 x 12.7 dia	26.0	11.82	PPM	SG	FA	8708H	
38.1 x 9.65 dia	13.0	5.91	PPM	G	FA	719H	
40.64 x 15.24 x 19.05	37.0	16.82	IS	SG	L	781H	
40.64 x 10.16 dia	13.0	5.91	PPM	SG	FA	790H	
45.72 x 8.38 dia	10.0	4.55	PPM	SG	FA	8725H	
43.18 x 11.43 dia	17.0	7.73	PPM	SG	L	8741H	
50.8 x 10.16 dia	18.0	8.18	PPM	SG	L	867H	
45.72 x 10.8 dia	19.0	8.64	PPM	CP	L	839H	**Ku-Band**
76.2 x 17.78 dia	65.0	29.55	IS	A	L	866H	
48.26 x 12.7 x 15.24	20.0	9.09	PPM	CP	L	605H	
50.8 x 15.24 dia	45.0	20.45	IS	SG	L	854H	
40.64 x 10.0 dia	15.0	6.82	PPM	SG	L	838H	
68.58 x 15.24 dia	30.0	13.64	PPM	SG	L	835H	
35.56 x 8.89 dia	15.0	6.82	PPM	SG	L	820H	
40.64 x 11.43 dia	14.0	6.36	PPM	G	L	830H	
35.56 x 10.0 dia	12.0	5.45	PPM	SG	L	861H	
45.72 x 10.16 dia	12.0	5.45	PPM	AG	L	▲982H	**mm-wave**

Table B—CW RADAR and ECM TWTs

	Model Number	Frequency Range (GHz)	Power Output (kW)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current Ik (A)	Dimensions L x W x H (Inches)
S-Band	551H	2.0-4.0	1.0	CW	30.0	-8.0	1.5	20.0 x 3.0 dia
	▲562H	2.0-4.0	1.0 p - 0.2 CW	0.05	30.0	-7.8	1.8-0.300	17.5 x 2.5 dia
C-Band	▲580H	4.0-8.0*	1.0 p - 0.1 CW	0.05	40.0-23.0	-9.5	1.2-0.300	20.0 x 4.0 x 3.2
	▲636H	4.4-5.0	10.0	CW	11.0	-15.0	2.0	36.0 x 12.0 dia
	▲8713H	7.5-10.2	1.0	CW	40.0	-9.8	1.2	24.0 x 6.0 dia
X-Band	▲869H	8.0-16.0*	1.0 p - 0.1 CW	0.05	40.0-20.0	-11.0	1.2-0.300	17.0 x 4.0 x 3.2
	▲8730H	9.0-18.0	0.2	CW	30.0	-9.5	0.3	17.0 x 3.0 x 2.8
	8731H	10.0-10.2	0.5	CW	40.0	-16.0	0.25	14.2 x 2.0 dia
Ku-Band	875H	13.6-14.0	5.0	CW	43.0	-18.5	1.5	2.0 x 6.0 dia
	▲832H	15.5-17.5	1.0	CW	30.0	-14.5	0.5	20.0 x 7.0 dia
mm-wave	▲819H	54.5-55.5	5.0	CW	20.0	-15.0	0.9	25.0 x 12.0 x 12.0
	920H	59.7-60.3	0.05	CW	35.0	-15.5	0.060	14.0 x 4.0 x 5.0

Table C—COMMUNICATION TWTs

	Model Number	Frequency Range (GHz)	Power Output (kW)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current Ik (A)	Dimensions L x W x H (Inches)
C-Band	663H	5.2-5.8	3.0	CW	46.0	-13.5	1.8	27.0 x 8.0 x 8.0
	670HA	5.925-6.425	0.050	CW	45.0	-3.75	0.095	11.2 x 2.0 x 2.4
	677H	5.925-6.425	0.125	CW	45.0	-6.5	0.170	16.0 x 2.8 x 2.8
	662H	5.925-6.425	0.400	CW	40.0	-8.0	0.420	22.1 x 4.2 x 3.4
	614H	5.925-6.425	8.0	CW	40.0	-18.0	2.8	34.0 x 7.5 dia
	745H	7.9-8.4	1.2	CW	30.0	-9.9	0.09	18.0 x 6.0 dia
	751H/103	7.9-8.4	40.0	0.014	50.0	-32.0	7.5	22.0 x 5.5 dia
	767H	7.9-8.4	3.0	CW	35.0	-13.4	1.48	21.0 x 6.1 dia
	792H	7.9-8.4	5.0	CW	35.0	-13.4	2.05	21.0 x 6.1 dia
	▲8723H	7.9-8.4	14.0	CW	38.0	-22.0	2.7	27.0 x 6.8 dia
	▲784H	7.9-8.4	8.0	CW	36.0	-18.0	2.2	24.0 x 6.1 dia
	8760H	7.9-8.4	0.6-1.2	CW	40.0	-13.2	0.72	26.0 x 6.3 dia
X-Band	8736H	7.9-8.4	0.050	CW	45.0	-3.9	0.110	11.2 x 2.0 x 2.4
Ku-Band	870H	14.0-14.5	5.0	CW	35.0	-19.0	1.7	30.0 x 7.0 dia
	▲8730H	14.0-14.5	0.2	CW	30.0	-9.0	0.260	17.0 x 3.0 x 3.0
	848HA	14.0-14.5	0.020	CW	50.0	-4.0	0.070	9.3 x 2.0 x 2.3
	881H	14.0-14.5	0.250	CW	45.0	-8.6	0.3	21.6 x 5.2 x 2.5
	876H	14.0-14.5	0.700	CW	43.0	-16.0	0.4	21.6 x 4.8 x 6.2
mm-wave	914H	30.0-31.0	0.2	CW	35.0	-16.0	0.070	18.0 x 4.0 dia
	913H	36.0-38.0	0.1	CW	45.0	-16.0	0.070	18.0 x 4.0 dia
	915H	43.0-45.0	0.25	CW	50.0	-22.0	0.088	18.0 x 4.0 dia
	▲812H	49.5-58.0	0.15	CW	12.0	-20.0	0.12	15.0 x 4.0 x 10.0
	▲813H	54.5-55.5	1.0	CW	25.0	-25.0	0.4	18.0 x 10.0 x 12.0
	▲814H	91.0-96.0	0.10	CW	25.0	-15.0	0.17	18.0 x 9.0 x 10.0

Table D—COMMUNICATION POWER AMPLIFIERS

	Amplifier Model Number	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)▲▲	Input Voltage (Vac.ϕ)	Dimensions W x H x D (Inches)
C-Band	9210H02▲	5.925-6.425	100.0	60.0	120/240 VAC; -48 VDC	19.0 x 5.25 x 20.0
	9040H02	5.925-6.425	40.0	44.0	120/240 VAC; -24/48 VDC	19 x 3.5 x 15.6
	9640H02	5.925-6.425	40.0	44.0	120/240 VAC; -24/48 VDC	19.0 x 14.0 x 25.0
	9240H02	5.925-6.425	350.0	70.0	120/230 VAC; 50/60 Hz 1 ϕ	19.0 x 21.0 x 24.0
	9740H02	5.925-6.425	350.0	70.0	120/230 VAC; 50/60 Hz 1 ϕ	19.0 x 48.0 x 30.0
	9740H02R-003	5.925-6.425	350.0/700.0	70.0	120/230 VAC; 50/60 Hz 1 ϕ	19.0 x 70.0 x 30.0
X-Band	9040H03	7.9-8.4	40.0	44.0	120/240 VAC; -24/48 VDC	19.0 x 3.5 x 15.6
Ku-Band	9020H04	14.0-14.5	20.0	50.0	120/240 VAC;-24/48 VDC	19.0 x 15.6 x 3.5
	9225H04	14.0-14.5	225.0	60.0	120/240 VAC;-50/60 Hz 1 ϕ	19.0 x 21.0 x 24.0
	9015H04	14.0-14.5	15.0	50.0	120/240 VAC; -24/48 VDC	19.0 x 3.5 x 15.6
	9260H04	14.0-14.5	600.0	60.0	208 VAC 3 ϕ	19.0 x 25.0 x 30.0

▲ Under development ‡ Electronic power conditioner § Pulsed 0.33% duty

Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number	
50.8 x 7.62 dia	22.0	10.0	Sol	A	L	551H	**S-Band**
44.45 x 6.35 dia	10.0	4.55	PPM	SG	L	▲562H	
50.8 x 10.16 x 8.13	10.0	4.55	PPM	SG	C	▲580H	**C-Band**
91.44 x 30.48 dia	175.0	79.55	IS	A	V	▲636H	
60.96 x 15.24 dia	57.0	25.41	IS	A	L	▲8713H	
43.18 x 10.16 x 8.13	10.0	4.55	PPM	SG	C	▲869H	**X-Band**
43.18 x 7.62 x 7.11	8.0	3.64	PPM	A	C	▲8730H	
36.07 x 5.08 dia	7.5	3.41	PPM	CP	L	8731H	
55.88 x 15.24 dia	60.0	27.27	IS	A	L	875H	**Ku-Band**
50.80 x 17.78 dia	65.0	29.55	IS	A	L	▲832H	
63.50 x 30.48 x 30.48	60.0	27.27	Sol	CP	L	▲819H	**mm-wave**
35.56 x 10.16 x 12.70	13.0	5.91	PPM	CP	C	920H	

Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number	
68.58 x 20.32 x 20.32	140.0	63.64	IS	A	L	663H	**C-Band**
28.45 x 5.08 x 6.1	4.0	1.82	PPM	—	FA	670HA	
40.64 x 7.1 x 7.1	6.0	2.72	PPM	A	FA	677H	
56.13 x 10.67 x 8.64	10.0	4.55	PPM	A	FA	662H	
86.36 x 19.05 dia	95.0	43.18	Sol	A	L	614H	
45.72 x 15.24 dia	42.0	19.09	Sol	A	L	745H	
55.88 x 13.97 dia	30.0	13.64	PPM	SG	L	751H/103	
53.34 x 15.49 dia	68.0	30.91	IS	A	L	767H	
53.34 x 15.49 dia	65.0	29.55	IS	A	L	792H	
68.58 x 17.27 dia	120.0	54.55	IS	A	L	▲8723H	
60.96 x 15.49 dia	80.0	36.36	IS	A	L	▲784H	
66.04 x 16.0 dia	40.0	18.18	PPM	A	FA	8760H	
28.45 x 5.08 x 6.1	4.0	1.82	PPM	—	FA	8736H	**X-Band**
26.20 x 17.78 dia	65.0	29.55	IS	A	L	870H	**Ku-Band**
43.18 x 7.62 x 7.62	10.0	4.55	PPM	A	FA	▲8730H	
23.62 x 5.08 x 5.84	4.0	1.82	PPM	—	FA	848HA	
54.86 x 13.21 x 6.35	11.0	5.0	PPM	A	FA	881H	
54.86 x 12.19 x 15.75	28.0	12.73	PPM	A	FA	876H	
45.72 x 10.16 dia	12.0	5.45	PPM	A	FA	914H	**mm-wave**
45.72 x 10.16 dia	12.0	5.45	PPM	A	FA	913H	
45.72 x 10.16 dia	12.0	5.45	PPM	A	L/FA	915H	
38.1 x 10.16 x 25.4	17.0	7.73	PPM	CP	L	▲812H	
45.72 x 25.4 x 30.48	50.0	22.73	Sol	CP	L	▲813H	
45.72 x 22.66 x 25.40	40.0	18.18	Sol	CP	L	▲814H	

Dimensions W x H x D (cm)	Weight (lbs.)	Weight (kg)	TWT Model Number	Type	Amplifier Model Number	
48.26 x 13.34 x 50.8	75.0	34.09	677H	Power Amplifier	9210H02▲	**C-Band**
48.26 x 8.89 x 39.62	30.0	13.64	670HA	Power Amplifier	9040H02	
48.26 x 35.56 x 63.5	90.0	40.91	670HA	Redundant Subsystem	9640H02	
48.26 x 53.34 x 60.96	170.0	77.27	662H	HPA	9240H02	
48.26 x 121.91 x 76.2	400.0	181.82	662H	Redundant Subsystem	9740H02	
48.26 x 177.8 x 76.2	400.0	181.82	662H	Redundant/ Pwr Combined Subsystem	9740H02R-003	
48.26 x 8.89 x 39.62	30.0	13.64	8736H	Power Amplifier	9040H03	**X-Band**
48.26 x 39.62 x 8.89	20.0	9.09	848HA	Power Amplifier	9020H04	**Ku-Band**
48.26 x 53.34 x 60.96	170.0	77.27	881H	HPA	9225H04	
48.26 x 8.89 x 39.62	30.0	13.64	848HA	Power Amplifier	9015H04	
48.26 x 63.5 x 76.2	200.0	90.91	876H	HPA	9260H04	

Table E—SPACE TYPE CW TWTs[1]

	Model Number	Frequency Range (GHz)	Power (W)	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current Ik (A)
L-Band	291H[6]	1.5-1.6	7.0/26.0/60.0	23, 33, 47	-2.63	0.014, 0.027, 0.057
	414H	1.5-2.0	12.0	28	-1.2	0.05
	222H	1.6-1.8	23.0	37	-27	0.044
S-Band	278H	2.0-2.1	26.0	44	-2.4	0.046
	8281H	2.0-2.3	300.0	35	4.9	0.170
	214H	2.2-2.4	8.0	27	-0.93	0.04
	283H	2.5-2.7	100.0	42	-3.3	0.1
	297H	2.5-2.7	50.0	4	-2.54	0.056
C-Band	235H	3.7-4.2	12.0	43	-1.8	0.04
	230H	3.7-4.2	5.5	55	-1.3	0.022
	244H	3.7-4.2	4.5	54	-1.3	0.022
	249H	3.7-4.2	8.5	57	-1.6	0.03
	271H	3.7-4.2	6.0	57	-1.2	0.025
	272H	3.7-4.2	1.5	35	-1.63	0.09
	275H	3.7-4.2	5.0	55	-1.3	0.022
	276H	3.7-4.2	0.5	31	-1.05	0.005
	277H	3.7-4.2	5.5	55	-1.35	0.025
	246H	3.7-4.2	12.0	57	1.8	0.35
	296H	3.7-4.2	5.0	55	-1.28	0.021
	8510H	3.7-4.2	7.5	58	-1.4	0.030
	8511H	3.7-4.2	9.5	58	-1.6	0.035
	279H	5.9-6.4	100.0	33	-3.6	0.085
X-Band	240H	6.0-9.0	20.0	40	-3.4	0.042
	240HA	6.0-9.0	16.0	46	-3.4	0.040
	263H	7.0-8.0	0.5	32	-1.75	0.005
	293H	7.0-8.0	40.0	53	-4.0	0.053
	298H	7.0-8.0	10.0	50	-2.6	0.026
	265H	7.0-9.0	22.0	46	-3.8	0.05
	287H	7.9-8.4	50.0	33	-4.25	0.057
	219H	8.0-9.0	20.0	40	-3.4	0.04
	285H	8.4-8.5	24.0	37	-3.3	0.036
Ku-Band	837H	10.0-15.0	1.2	45	-1.86	0.009
	280H	10.5-13.0	10.0	54	-3.0	0.029
	286H	11.0-12.0	12.0	47	-2.93	0.03
	▲286H	11.0-12.0	20.0	57	-4.06	0.038
	289H	11.7-12.2	20.0	50	-3.6	0.040
	837HD	11.9-12.1	1.3	45	-1.88	0.01
	845H	11.9-13.8	1.5	44	-2.0	0.01
	294H[2,4]	11.95-12.13	100.0	40	-8.1	0.056
	837HA	12.0-16.0	1.0	45	-1.84	0.009
	284H[2,4]	12.038-12.123	250.0	38	-8.2	0.092
	295H	13.0-14.0	20.0	48	-3.45	0.042
	837HB	13.0-14.0	1.0	45	-1.85	0.009
	851H	13.5-14.0	20.0	53	-3.55	0.05
	837HC	13.7-14.1	1.0	45	-1.88	0.01
	874H	13.8-15.0	60.0	47	-5.0	0.075
	264H	14.0-15.0	16.0	46	-3.45	0.041
	288H	14.0-15.0	16.0	46	-3.45	0.042
	8294H[3,4]	14.52-14.68	100.0	40	-8.0	0.056
	288HC	14.85-15.15	15.0	45	-3.4	0.04
	292H	17.75-20.25	4.0	50	-4.5	0.017
K-Band	▲882H	17.0-22.0	15.0	45	-6.0	0.030
	▲918H	17.0-22.0	25/75	20/50	-11.0	0.075
	268H	18.0-22.0	2.0	42	-3.9	0.013
	950H[6]	19.0-23.0	3.5/7.0/15/30	55	-6.75	0.05
mm-wave	950HA	22.0-32.0	10.0	46	-6.0	0.030
	254H	29.0-31.0	2.0	42	-5.5	0.007
	251H	30.0-32.0	3.0	43	-5.4	0.012
	▲943H[5]	41.0-43.0	200.0	47	-21.0	0.095
	▲944H	42.0-42.5	100.0	44	-14.5	0.046
	▲985H[5]	84.0-86.0	200.0	47	-25.0	0.160

▲ = under development

[1] All models are PPM focused and conduction cooled unless otherwise noted

[2] Anode mod control [3] Aperature grid [4] Conduction radiation cooling [5] Radiation cooling [6] Multi-power levels

Dimensions L x W x H (Inches)	Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Model Number	
20.2 x 4.3 x 2.7	51.31 x 10.92 x 6.86	9.0	4.09	291H[6]	**L-Band**
11.5 x 1.6 x 1.6	29.21 x 4.06 x 4.06	1.4	0.64	414H	
17.5 x 2.5 x 2.77	44.45 x 6.35 x 7.04	4.2	1.91	222H	
17.5 x 2.25 x 2.5	44.45 x 5.72 x 6.35	5.0	2.27	278H	**S-Band**
22.0 x 7.5 x 4.3	55.88 x 19.05 x 10.92	12.0	5.45	8281H	
8.25 x 3.0 x 1.1	20.96 x 7.62 x 2.79	1.0	0.45	214H	
14.5 x 2.6 x 3.0	36.83 x 6.60 x 7.62	4.2	1.91	283H	
15.0 x 2.0 x 2.0	38.10 x 5.08 x 5.08	3.5	1.59	297H	
11.0 x 1.6 x 1.4	27.94 x 4.06 x 3.56	1.2	0.55	235H	**C-Band**
12.4 x 1.9 x 2.3	31.50 x 4.83 x 5.84	1.25	0.57	230H	
12.4 x 1.9 x 2.3	31.5 x 4.83 x 5.84	1.6	0.73	244H	
13.0 x 1.9 x 2.3	33.02 x 4.83 x 5.84	1.7	0.77	249H	
12.3 x 1.9 x 1.8	31.24 x 4.83 x 4.57	1.75	0.80	271H	
12.0 x 1.9 x 1.84	30.48 x 4.83 x 4.67	1.31	0.60	272H	
12.0 x 1.9 x 1.75	30.48 x 4.83 x 4.45	1.5	0.68	275H	
10.2 x 1.9 x 1.84	25.91 x 4.83 x 4.67	1.2	0.55	276H	
12.0 x 2.3 x 1.8	30.48 x 5.84 x 4.57	1.5	0.68	277H	
14.0 x 2.0 x 2.0	35.56 x 5.08 x 5.08	1.8	0.82	246H	
12.1 x 1.9 x 2.3	30.73 x 4.83 x 5.84	1.4	0.64	296H	
14.0 x 2.0 x 2.0	35.56 x 5.08 x 5.08	1.8	0.82	8510H	
14.0 x 2.0 x 2.0	35.56 x 5.08 x 5.08	1.8	0.82	8511H	
12.0 x 2.5 x 2.5	30.48 x 6.35 x 6.35	3.0	1.36	279H	
12.3 x 3.0 x 1.5	31.24 x 7.62 x 3.81	2.75	1.25	240H	**X-Band**
12.5 x 4.6 x 2.2	31.75 x 11.68 x 5.59	3.1	1.41	240HA	
9.6 x 1.1 x 1.4	24.38 x 2.79 x 3.56	1.0	0.45	263H	
13.25 x 2.5 x 2.5	33.66 x 6.35 x 6.35	3.6	1.63	293H	
11.4 x 2.18 x 1.7	28.96 x 5.5 x 4.32	1.5	0.68	298H	
12.0 x 2.2 x 1.3	30.48 x 5.59 x 3.30	2.2	1.00	265H	
11.7 x 1.6 x 2.0	29.72 x 4.06 x 5.08	2.25	1.02	287H	
10.5 x 2.3 x 1.7	26.67 x 5.84 x 4.32	1.5	0.68	219H	
11.7 x 1.6 x 2.0	29.72 x 4.06 x 5.08	2.25	1.02	285H	
9.4 x 1.7 x 1.8	23.88 x 4.32 x 4.57	1.2	0.55	837H	**Ku-Band**
9.8 x 1.9 x 1.6	24.89 x 4.83 x 4.06	1.25	0.57	280H	
10.0 x 2.0 x 2.0	25.4 x 5.08 x 5.08	1.8	0.81	286H	
13.0 x 2.0 x 2.0	33.02 x 5.08 x 5.08	2.0	0.91	▲286HP	
13.0 x 2.0 x 2.0	33.02 x 5.08 x 5.08	1.7	0.75	289H	
9.4 x 1.7 x 1.8	23.88 x 4.32 x 4.57	1.2	0.55	837HD	
11.0 x 1.9 x 2.6	27.94 x 4.83 x 6.60	1.8	0.81	845H	
21.0 x 6.0 dia	53.34 x 15.24 dia	14.6	6.64	294H[2,4]	
10.0 x 1.9 x 2.7	25.40 x 4.83 x 6.86	1.4	0.64	837HA	
18.0 x 9.8 dia	45.72 x 24.89 dia	26.2	11.91	284H[2,4]	
10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.4	1.09	295H	
9.4 x 1.7 x 1.8	23.88 x 4.32 x 4.57	1.2	0.55	837HB	
10.0 x 1.9 x 2.7	25.40 x 4.83 x 6.86	1.63	0.74	851H	
10.3 x 1.9 x 2.3	26.16 x 4.83 x 5.84	1.4	0.64	837HC	
14.0 x 4.0 x 3.0	35.56 x 10.16 x 7.62	6.0	2.73	874H	
10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.5	1.14	264H	
10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.4	1.09	288H	
21.0 x 6.0 dia	53.34 x 15.24 dia	14.6	6.64	8294H[3,4]	
10.25 x 2.65 x 1.85	26.04 x 6.73 x 4.70	2.4	1.09	288HC	
12.0 x 1.5 x 1.5	30.48 x 3.81 x 3.81	1.9	0.86	292H	
13.0 x 2.5 x 3.0	33.02 x 6.35 x 7.62	2.2	1.0	▲882H	**K-Band**
16.0 x 3.0 x 3.0	40.64 x 7.62 x 7.62	6.0	2.73	▲918H	
9.6 x 1.8 x 2.0	24.38 x 4.57 x 5.08	1.2	0.55	268H	
13.5 x 3.0 x 3.0	34.29 x 7.62 x 7.62	2.0	0.91	950H[6]	
13.5 x 3.0 x 3.0	34.29 x 7.62 x 7.62	2.0	0.91	950HA	**mm-wave**
10.0 x 1.9 x 1.9	24.50 x 4.83 x 4.83	1.2	0.55	254H	
12.4 x 2.5 x 2.0	31.50 x 6.35 x 5.08	1.8	0.82	251H	
14.0 x 5.0 x 5.0	35.56 x 12.70 x 12.70	15.0	6.82	▲943H[5]	
17.0 x 5.0 x 5.0	43.18 x 12.70 x 12.70	15.0	6.82	▲944H	
18.0 x 6.0 x 6.0	45.72 x 15.24 x 15.24	18.0	8.18	▲985H[5]	

Table F—SPACE TYPE CW TWTAs

	Amplifier Model Number	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Input Voltage (Vdc)	Dimensions L x W x H (Inches)
S-Band	1266H	2.0-2.1	26.0	44	22-42	13.7 x 3.0 x 4.0
	1190H	2.2-2.3	15.0	30	22-32	11.0 x 6.0 x 4.2
	1272H	2.5-2.7	50.0	47	23-42	14.0 x 6.0 x 5.0
C-Band	1243H	3.7-4.2	4.5	54	22-42	13.5 x 4.0 x 3.25
	1244H	3.7-4.2	8.5	57	22-42	13.25 x 4.0 x 3.25
	1253H	3.7-4.2	8.5	57	50 ± 2%	13.25 x 4.0 x 3.25
	1264H	3.7-4.2	5.5	55	22-40	13.23 x 4.3 x 3.2
	1288H	3.7-4.2	5.0	53	24-36	13.3 x 3.5 x 3.3
	1224H	4.1-4.2	0.2	51	28 ± 2%	11.0 x 3.5 x 1.7
X-Band	1240H	6.0-10.0	20.0	48	22-33	12.0 x 6.1 x 4.1
	1200H	7.0-8.0	0.5	32	23-33	10.0 x 4.0 x 2.5
	1238H	7.0-8.0	40.0	53	22-33	15.15 x 6.0 x 4.7
	1241H	7.0-8.0	40.0	53	22-33	15.15 x 6.0 x 4.7
	1202H	7.0-9.0	22.0	46	23-33	12.0 x 5.0 x 3.0
	1248H	7.25-7.75	10.0	50	22-33	13.6 x 4.3 x 4.3
	1255H	7.25-7.75	40.0	53	22-33	15.15 x 6.0 x 4.7
Ku-Band	1292H	11.9-12.1	1.0	45	26-29	11.4 x 5.1 x 2.6
	1268H	11.9-13.8	1.5	55	22-42	13.25 x 4.0 x 3.25
	1247H	11.7-12.2	20.0	57	21-35	12.75 x 5.0 x 4.2
	1250H	13.0-14.0	20.0	48	23-35	13.0 x 4.4 x 3.7‡
	1256H	13.25-13.75	2000§	43	24-33	16.25 x 6.75 x 6.25‡
	1218H	13.5-14.5	1.5	40	24-30	11.0 x 5.7 x 2.5
	1220H	13.5-14.5	20.0	53	24-30	12.0 x 6.5 x 4.25
	1230H	14.0-15.0	16.0	46	23-35	13.0 x 4.4 x 3.7‡
	1260H	14.0-15.0	16.0	46	23-35	13.0 x 4.4 x 3.7‡
	1294H	17.75-20.25	4.0	50	24-32	13.25 x 4.2 x 3.5
mm-wave	1254H	30.0-32.0	3.0	43	2.8-29.6	13.25 x 4.4 x 3.4

Table G—TWT AMPLIFIERS

	Amplifier Model Number	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Input Voltage (Vac ϕ)	Dimensions L x W x H (Inches)
S-Band	1233H	2.0-4.0	8.0	35	208.3	19.0 x 6.5 x 7.0
	1160H	2.9-3.1	3000§	70	115.3	20.0 x 4.0 x 8.0
C-Band	1234H	4.0-8.0	20.0	38	208.3	19.0 x 6.5 x 7.0
X-Band	1235H	8.0-12.4	4.0	33	208.3	19.0 x 6.5 x 7.0
Ku-Band	1236H	12.4-18.0	5.0	37	208.3	19.0 x 6.5 x 7.0
mm-wave	1228H	37.0-38.0	2.0	30	28-34 Vdc	13.5 x 8.0 x 3.5

§ Pulsed
‡ Power Supply Dimension Only

Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	TWT Model Number	Amplifier Model Number	
34.93 x 7.62 x 10.16	7.5	3.41	278H	1266H	**S-Band**
27.94 x 15.24 x 10.67	8.5	3.86	256H	1190H	
35.56 x 15.24 x 12.70	9.0	4.09	297H	1272H	
33.66 x 10.16 x 8.26	4.6	2.09	244H	1243H	**C-Band**
33.66 x 10.16 x 8.26	5.0	2.27	249H	1244H	
33.66 x 10.16 x 8.26	3.1	1.41	249HA	1253H	
33.60 x 10.92 x 8.13	3.0	1.36	230H	1264H	
33.78 x 8.89 x 8.38	3.75	1.70	296H	1288H	
27.94 x 8.9 x 4.32	2.7	1.23	233HC	1224H	
30.48 x 15.5 x 10.41	9.6	4.36	265HA	1240H	**X-Band**
25.4 x 10.16 x 6.35	4.5	2.05	263H	1200H	
38.48 x 15.24 x 11.94	15.75	7.16	293H	1238H	
38.48 x 15.24 x 11.94	16.5	7.5	293HA	1241H	
30.48 x 12.7 x 7.62	9.5	4.32	265H	1202H	
34.54 x 10.92 x 10.92	6.5	2.95	298H	1248H	
38.48 x 15.24 x 11.94	15.0	6.82	293HB	1255H	
28.96 x 12.95 x 6.6	4.4	2.00	837HD	1292H	**Ku-Band**
33.66 x 10.16 x 8.26	3.5	1.59	845H	1268H	
32.39 x 12.70 x 10.67	7.5	3.41	286HP	1247H	
33.02 x 11.18 x 9.4	7.0‡	3.18	295H	1250H	
41.28 x 17.15 x 15.88	30.0	13.64	853H	1256H	
27.94 x 14.48 x 6.35	6.0	2.73	837HA	1218H	
30.48 x 16.51 x 10.8	9.25	4.20	851H	1220H	
33.02 x 11.18 x 9.4	7.0‡	3.18	288H	1230H	
33.02 x 11.18 x 9.4	7.0‡	3.18	264H	1260H	
33.66 x 10.67 x 8.89	4.8	2.18	292H	1294H	
33.66 x 11.18 x 8.64	5.5	2.50	251H	1254H	**mm-wave**

Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	TWT Model Number	Amplifier Model Number	
48.26 x 16.51 x 17.78	18.5	8.41	564H-8	1233H	**S-Band**
50.8 x 10.16 x 20.32	28.0	12.72	543H - 544H	1160H	
48.26 x 16.51 x 17.78	18.5	8.41	640H-8	1234H	**C-Band**
48.26 x 16.51 x 17.78	18.5	8.41	771H-8	1235H	**X-Band**
48.26 x 16.51 x 17.78	18.5	8.41	848H-8	1236H	**Ku-Band**
34.29 x 20.32 x 8.89	8.0	3.64	863H	1228H	**mm-wave**

Table H—INSTRUMENTATION POWER AMPLIFIERS

	Amplifier Model Number	Frequency Range (GHz)	Power Output (W)	Saturated Gain (dB)	Dimensions L x W x H (Inches)	Dimensions L x W x H (cm)
L-Band	1177H09F000	1.0-2.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1277H09F000	1.0-2.0	20.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H10F000	1.4-2.4	20.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
S-Band	1177H01F000	2.0-4.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1277H01F00	2.0-4.0	20.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H05F000	2.5-4.0	20.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
C-Band	1177H13F000	3.0-8.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H16F000	3.9-11.7	10.0*	30*	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H02F000	4.0-8.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1277H02F000	4.0-8.0	20.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H06F000	4.0-10.5	10.0	30*	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H14F000	5.0-10.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H07F000	6.5-13.5	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H17F000	7.0-16.5	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
X-Band	1177H03F000	8.0-12.4	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1277H03F000	8.0-12.4	20.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H15F000	8.0-18.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1177H08F000	10.5-18.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
Ku-Band	1177H04F000	12.4-18.0	10.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
	1277H04F000	12.4-18.0	20.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
K-Band	1077H11F000	18.0-26.5	1.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89
Ka-Band	1077H12F000	26.5-40.0	1.0	30	15.5 x 16.75 x 3.5	39.37 x 42.55 x 8.89

Note: Each amplifier contains a PPM-focused, metal-ceramic TWT, all solid-state, air-cooled power supply in a 19-inch instrument case.

Options: Isolator/circulators, high gain, and automatic reset. 220/240 ac or 28/48 dc input voltage, unattended protection, rack mounting, local/remote, 48 to 420 Hz, logic circuit (TTL).

Warranty: One year regardless of operating hours.

* Slightly lower at band edges.

Table I—KLYSTRONS

	Model Number	Frequency Range (GHz)	Minimum Power Output (kW)	Duty Cycle	Saturated Gain (dB)	Cathode Voltage Ek (kV)	Cathode Current Ik (A)	Dimensions L x W x H (Inches)
X-Band	173H	9.2-9.4	0.1	0.33	30.0	-3.0	0.15	5.0 x 3.5 x 3.5
	793H	9.2-9.4	0.1	0.33	40.0	-3.0	0.15	5.0 x 3.5 x 3.5
	8710H	9.2-9.4	0.1	0.33	40.0	-3.0	0.15	5.0 x 3.5 x 3.5
	8734H	9.2-9.4	0.1	0.5	30.0	-3.3	0.20	5.0 x 3.5 x 3.5
	173H Mod.	10.0-10.25	0.2	CW	40.0	-3.6	0.22	6.0 x 4.0 x 4.0
Ku-Band	8702H	12.6-12.9	0.036	CW	40.0	-2.0	0.10	6.0 x 3.9 x 5.5

SYMBOLS

A = mod anode
AG = Aperture Grid
C = conduction
CP = cathode pulse
FA = forced air
G = high mu grid
IS = integral solenoid
L = liquid
PM = permanent magnet
PPM = periodic-permanent magnet
SG = shadow grid
Sol = solenoid
V = vapor phase

Weight (pounds)	Weight (kg)	Connector Type	Input Voltage (Vac. 1 ϕ)	Input Frequency (A)	TWT Model Number	Amplifier Model Number	
25.0	11.36	N	115.0	50/60	417H	1177H09F000	**L-Band**
25.0	11.36	N	115.0	50/60	418H	1277H09F000	
20.0	9.09	N	115.0	50/60	419H	1177H10F000	
20.0	9.09	N	115.0	50/60	564H	1177H01F000	**S-Band**
20.0	9.09	N	115.0	50/60	568H	1277H01F000	
20.0	9.09	N	115.0	50/60	564HS	1177H05F000	
20.0	9.09	N	115.0	50/60	646H	1177H13F000	**C-Band**
20.0	9.09	N	115.0	50/60	664H	1177H16F000	
20.0	9.09	N	115.0	50/60	648H	1177H02F000	
20.0	9.09	N	115.0	50/60	640H	1277H02F000	
20.0	9.09	N	115.0	50/60	648HS	1177H06F000	
20.0	9.09	N	115.0	50/60	746H	1177H14F000	
20.0	9.09	N	115.0	50/60	771HS	1177H07F000	
20.0	9.09	SMA	115.0	50/60	785H	1177H17F000	
20.0	9.09	N	115.0	50/60	771H	1177H03F000	**X-Band**
20.0	9.09	N	115.0	50/60	783H	1277H03F000	
20.0	9.09	SMA	115.0	50/60	846H	1177H15F000	
20.0	9.09	SMA or WR-62	115.0	50/60	848HS	1177H08F000	
20.0	9.09	SMA or WR-62	115.0	50/60	848H	1177H04F000	**Ku-Band**
20.0	9.09	WR-62	115.0	50/60	856H	1277H04F000	
20.0	9.09	WR-42	115.0	50/60	911H	1077H11F000	**K-Band**
20.0	9.09	WR-28	115.0	50/60	912H	1077H12F000	**Ka-Band**

Dimensions L x W x H (cm)	Weight (lbs.)	Weight (kg)	Focusing	Modulation Control	Cooling	Model Number	
12.7 x 8.89 x 8.89	4.5	2.05	PM	CP	L	173H	**X-Band**
12.7 x 8.89 x 8.89	4.5	2.05	PM	CP	FA	793H	
12.7 x 8.89 x 8.89	4.5	2.05	PM	G	FA	8710H	
12.7 x 8.89 x 8.89	4.5	2.05	PM	G	C	8734H	
15.24 x 10.16 x 10.16	5.0	2.27	PM	CP	FA	173H Mod.	
15.24 x 9.1 x 13.97	7.25	3.30	PM	CP	FA	8702H	**Ku-Band**

Cross Index of Models

Model No.	Table	Page No.
866H	A	44
867H	A	44
869H	A/B	44/46
870H	C	46
874H	E	48
875H	B	46
876H	C	46
881H	C	46
882H	E	48
913H	C	46
914H	C	46
915H	C	46
918H	E	48
920H	B	46
943H	E	48
944H	E	48
950H	E	48
950HA	E	48
982H	A	44
985H	E	48
1160H	G	50
1190H	F	50
1200H	F	50
1202H	F	50
1218H	F	50
1220H	F	50
1224H	F	50
1228H	G	50
1230H	F	50
1233H	G	50
1234H	F/G	50
1235H	G	50
1236H	G	50
1238H	F	50
1240H	F	50
1241H	F	50
1244H	F	50
1247H	F	50
1248H	F	50
1250H	F	50
1253H	F	50
1254H	F	50
1255H	F	50
1256H	F	50
1260H	F	50
1264H	F	50
1266H	F	50
1268H	F	50
1272H	F	50
1288H	F	50
1292H	F	50
1294H	F	50
8281H	E	48
8294H	E	48
8503H	A	44
8510H	E	48
8511H	E	48
8702H	I	52
8708H	A	44
8709H	A	44
8710H	I	52
8713H	B	46
8715H	A	44
8716H	A	44
8718H	A	44
8723H	C	46
8725H	A	44
8730H	C/B	46
8731H	B	46
8734H	I	52
8736H	C	46
8740H	A	44
8741H	A	44
8753H	A	44
8754H	A	44
8760H	C	46
9015H04	D	46
9020H04	D	46
9040H02	D	46
9040H03	D	46
9040H04	D	46
9210H02	D	46
9225H04	D	46
9240H02	D	46
9260H04	D	46
9640H02	D	46
9740H02	D	46
9740H02R-003	D	46
1077H11F000	H	52
1077H12F000	H	52
1177H01F000	H	52
1177H02F000	H	52
1177H03F000	H	52
1177H04F000	H	52
1177H05F000	H	52
1177H06F000	H	52
1177H07F000	H	52
1177H08F000	H	52
1177H09F000	H	52
1177H10F000	H	52
1177H13F000	H	52
1177H14F000	H	52
1177H15F000	H	52
1177H16F000	H	52
1177H17F000	H	52
1277H01F000	H	52
1277H02F000	H	52
1277H03F000	H	52
1277H04F000	H	52
1277H09F000	H	52

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MSN

New Developments in High Power Coupled-Cavity Traveling-Wave Tubes for Communications Systems

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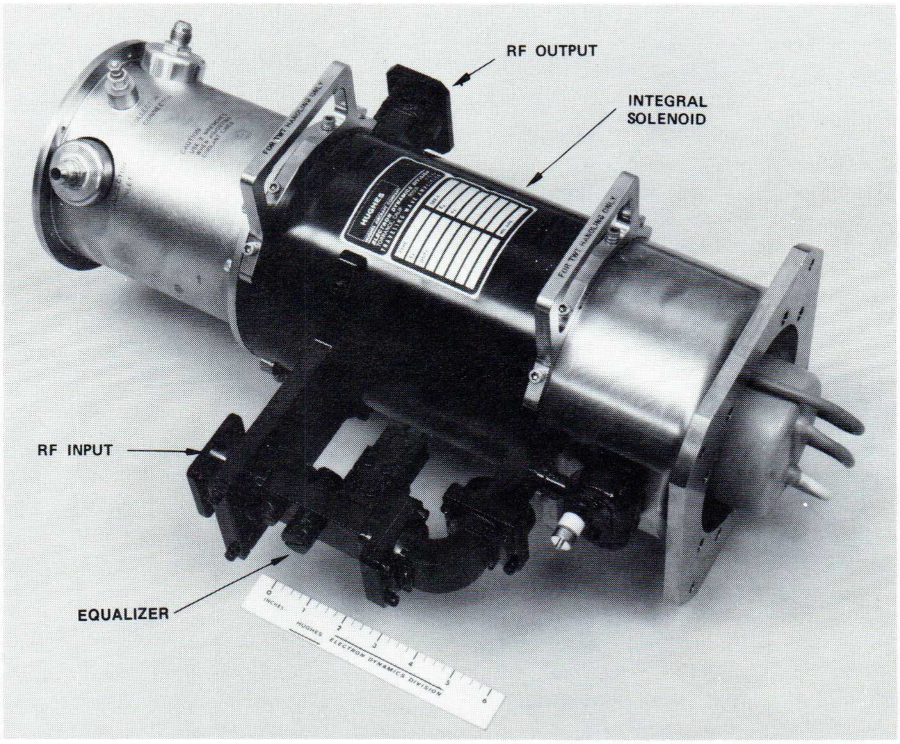


Figure 1. Hughes 792H 5-kW X-band communications TWT

New microwave communication systems developments, both terrestial and satellite, have produced needs for high power RF amplifiers with greatly improved performance characteristics. Amplifiers with higher output power, greater efficiency, increased instantaneous bandwidth, less signal distortion, reduced cooling requirements and longer operating life are needed to meet the performance and cost objectives of these systems. To keep pace with these new requirements, Hughes Aircraft Company/Electron Dynamics Division has developed several new techniques for high power coupled-cavity traveling-wave tubes (TWT's). This article describes the design and performance of two TWT's that utilize these new techniques and which exemplify the present state of the art in high power communications RF amplifiers.

The first tube, Model 792H, was developed for use as the final power amplifier in the MSC-60 military satellite communications ground stations. It operates over the 7.90 to 8.40 GHz frequency band, producing 0 to 5 kilowatts of RF output power. For such communication systems low distortion is required at all output power levels since the overall system performance is in large part determined by the output TWT's performance. Extremely low amplitude and phase ripple is achieved by means of special tube construction techniques and an integral gain equalizer.

The second tube, the 294H, is a 100-watt, coupled-cavity space TWT operating at 12.0 GHz. Over 50 percent efficiency is obtained using an RF circuit velocity taper and a three-stage depressed collector. To reduce the thermal load on the satellite, the collector is cooled by direct radiation to keep space.

The 792H, a low distortion 5-KW TWT. Model 792H coupled-cavity communications TWT is shown in Figure 1. This tube is used in the MSC-60 ground stations; in this new system, two 5-kilowatt 792H amplifiers replace an 8-kilowatt narrow-band klystron amplifier and a 3-kilowatt TWT previously used. The MSC-60 was originally configured to amplify two or more FM modulated carriers using the 3-kW TWT at 10 dB or more below saturated output for low intermodulation products. In the event of a hostile jamming threat, the system could be switched to a single-carrier high output operating mode using the 8-kW klystron.

In the new system configuration, one 792H amplifier is normally operational, while the redundant tube is kept in standby. In the event of a transmitter shut-down, the standby unit can be immediately activiated, resulting in minimum system downtime. The anti-jam capability is provided by power combining the 5-kW saturated output of both amplifiers. With the phase tracking characteristics of the 792H's, this can be easily accomplished over a 400-MHz bandwidth. This approach not only improves the system reliability and bandwidth, it results in significant cost savings and better maintainability by using two identical amplifier/power supply units rather than two entirely different ones.

Special construction techniques used. The 792H TWT uses a coupled-cavity RF circuit, a modulating anode electron

An in-depth look at the state of the art in communication TWT's as exemplified by two advanced designs—a 12-GHz space tube and an 8-GHz earth station model.

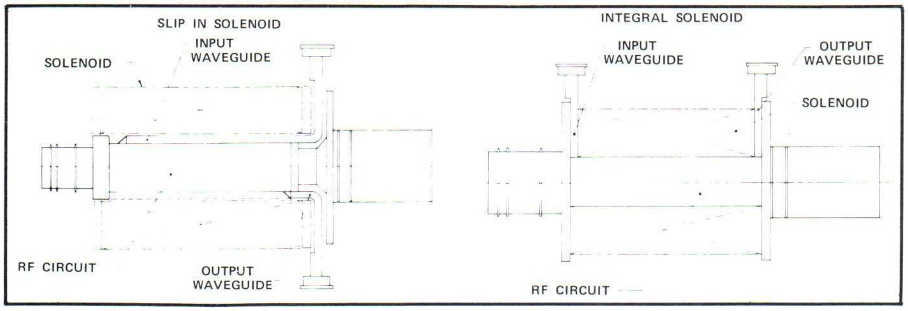


Figure 2. Slip-in and integral solenoid focused coupled-cavity TWT's

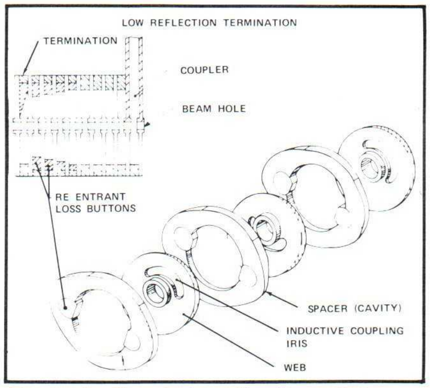


Figure 3. Coupled cavity slow-wave circuit

gun and a high power non-depressed collector. Rugged metal ceramic construction is used throughout the tube. The 28-kW electron beam is focused with an integral solenoid, built directly on the RF circuit. This solenoid design has several important advantages when compared with the conventional slip-in solenoid, both shown in Figure 2. The integral solenoid is smaller and lighter and requires less power, since the inside diameter is only as large as the RF circuit; the slip-in design must be large enough to clear the gun and waveguides. The tube axis and magnetic field axis are exactly aligned resulting in nearly perfect focusing, thereby reducing the current load on the cathode power supply and permitting the use of simple relay TWT body over-current protection circuits. Input and output waveguide couplers are brought out radially instead of being bent along the circuit of the TWT, greatly reducing the mismatches and giving rise to improved amplitude and phase characteristics.

The TWT body, solenoid and collector are cooled with water or an ethylene glycol/water mixture. Large coolant passages in the body and collector and enclosed coolant lines in the solenoid permit the use of filtered water having high levels of impurities with no significant reduction in tube life. The long, narrow coolant ducts used in most TWT's can become easily clogged, a condition that usually leads to relatively rapid and catastrophic tube failure.

Typical operating parameters of the 792H are given in Table I. The 18%, undepressed efficiency is typical of communications TWT's, as high system efficiency is not required. By depressing the collector, the TWT efficiency can be increased to 30 percent.

An all copper, coupled-cavity slow-wave circuit is used in this tube. This circuit is comprised of many re-entrant cylindrical cavities inductively coupled by kidney-shaped irises to provide the basic interaction between the electron beam and the RF wave. A typical circuit section is shown in Figure 3. The coupled-cavity circuit's gain, bandwidth, and high thermal capability makes it the logical choice for multi-kilowatt tubes.

Overall high gain with stability is achieved by dividing the interaction circuit into three sections. The RF circuit wave is absorbed at the ends of each section in well-matched internal terminations. The sections are coupled in the forward direction only by the RF modulated electron beam. The regenerative effects, that can cause gain variations result from imperfect matches in the interaction circuit; these effects are greatly reduced when confined to individual circuit sections.

Special emphasis to minimizing gain and phase fine structure is given in the design of the circuits for the 792H. Gain and phase variations result from feedback caused by mismatches in the circuit section. The principal mismatches occur at the ends of the sections, i.e. the internal terminations and the input and output RF waveguide couplers. The larger the mismatches at these points and the higher the gain in each circuit section, the greater will be the gain and phase variations. A three-section circuit is used in the 792H to minimize the gain per section yet maintain reasonable efficiency.

The internal terminations normally used in coupled-cavity circuits are of relatively short electrical length, being confined to a single cavity. As a result the mismatch of these terminations can only be reduced to a low but imperfect level. Hughes has developed and patented a tapered internal termination for coupled-cavity circuits that extends over several cavities. The long electrical length of this termination and the gradually tapering loss pattern results in a very low mismatch. This technique also introduces in-band loss in the section, further reducing the feedback effect. The tapered loss is obtained by using small cavities adjacent to the circuit cavity; these cavities, are loaded with lossy ceramic "buttons" that protrude significantly into the cavity. The protrusion or re-entrancy of a button determines the amount of in-band loss, with the more re-entrant buttons providing more loss. The amount of loss is easily tapered in successive cavities by simply changing the amount of button re-entrancy. The tapered termination is illustrated in Figure 3.

This special termination is used in the 792H circuit to obtain the lowest

Table I

792H Operating Parameters

RF	
Frequency	7.90–8.40 GHz
Output Power	0–5 kW
Gain	40 dB Min.
ELECTRICAL	
Beam Voltage	−13.5 kV dC
Beam Current	2.10 A dC
Solenoid Voltage	185 Vdc
Solenoid Current	10 Adc
Body Current (no rf)	10 MA
Body Current (with rf)	50 MA
MECHANICAL	
Diameter	7.0 Inches Dia.
Length	21.0 Inches
Weight	66 Lbs.
Cooling	7 GPM Ethylene Glycol/Water

possible output section mismatches, which are primarily responsible for gain and phase variations, as this section has significantly more gain than the others.

Other mismatches are also avoided. In order to reduce the RF waveguide coupler mismatches, the waveguide bends and mitered corners are eliminated by use of integral solenoid focusing as already described. These sharp bends typically cause larger mismatches than any other discontinuity in a TWT using a slip-in solenoid. Precision circuit parts and computer-aided matching techniques are also employed to minimize the smaller, but still significant, circuit mismatches.

Performance characteristics. The utilization of the techniques discussed produces a TWT gain response in the 792H with very little amplitude ripple. A comparison in Figure 4 of the small signal gain-frequency variation with a typical coupled-cavity radar tube indicates the smooth parabolic characteristic that is achieved.

To obtain the desired constant amplitude response, a simple single-pole external gain equalizer is used. By adjusting the transmission loss of the equalizer to be the inverse of the TWT gain-frequency curve, the overall variation is reduced below 0.60 dB across the entire 7.90 to 8.40 GHz band. Typical 792H characteristics are shown in Figure 5 for three output power levels—0, 10 and 20 dB down from saturation. Maximum amplitude variations over 40-, 125- and 500-MHz bands are 0.30 dB, 0.40 dB, and 0.60 dB, respectively.

Use of an external equalizer also improves the tube's phase linearity characteristics. Figure 6 shows the phase linearity versus frequency at 10 dB below saturation; the maximum phase deviations in the 40 MHz and 125 MHz bands are 1.0 degrees and 2.0 degrees, respectively. The coincident improvement of both amplitude and phase characteristics with a single external equalizer is due to the fact that both variations result from the mismatches within the TWT. The simplicity of the equalizer makes it relatively insensitive to external influences such as coolant temperature fluctuations or source and load VSWR.

The performance achieved on the 792H is not unique; similar characteristics have been achieved with Hughes TWT's up to 8 kW.

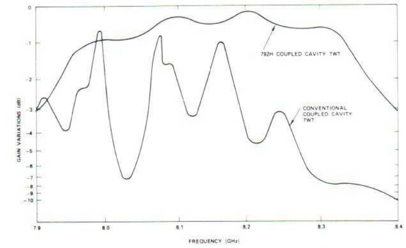


Figure 4. Small signal gain variations

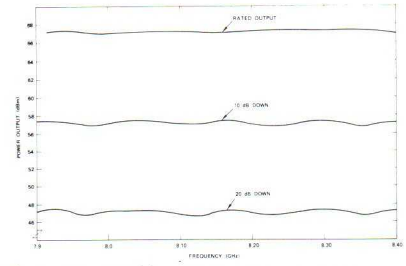


Figure 5. 792H swept output power

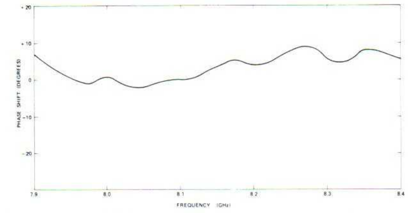


Figure 6. 792 phase linearity 10 dB down

High efficiency 100-watt TWT: Model 294H. The 294H is a 50-percent efficient, high reliability traveling-wave tube developed for use on direct broadcast communications satellite transponders. A photograph of the tube is shown in Figure 7. This TWT produces 120 watts of CW output power with 45 dB gain over a 180-MHz band at 12 GHz. It utilizes a coupled-cavity slow-wave circuit with two-step velocity tapering and a three-stage depressed collector to achieve the highest possible efficiency and the lowest heat dissipation. To further minimize the heat load on the satellite, the collector is thermally isolated from the tube and is cooled by direct radiation to deep space. In such a high power TWT, it is the collector that dissipates the most heat, particularly when no RF drive is applied.

Use of a coupled-cavity TWT is a new development in satellite transponder design, brought about by the need for hundreds of watts output in the 12 GHz band. The combination of power and frequency greatly reduces the reliability margin of a TWT using a helix structure due to the very small size (and thermal capability) of that type of slow-wave circuit at 12 GHz. However, CW power levels up to 1 kW present no problem for the larger, all-metal, coupled-cavity circuit. The high ERP of the new commercial broadcast satellites permits the use of inexpensive ground terminals for TV and voice transmission to small remote community distribution centers or even individual homes. Such an approach is particularly suitable in areas where the geography makes transmission cables or terrestrial microwave lines technically or economically impractical.

This tube is operated at saturation to amplify a single-carrier FM television signal. Multiple-carrier operation is also possible at reduced output power to lower the level of the intermodulation products. Similar to the ground terminal TWT's, amplitude and phase flatness with frequency are also important characteristics.

Tube prime input power, heat dissipation, and weight are as important as RF performance to the overall transponder design. A high power coupled-cavity TWT is significantly heavier than a helix tube due to the larger, all-metal slow-wave structure. However, these same features produce much higher reliability. The high efficiency and low thermal dissipation of the tube result in lower weight in the satellite because solar panel and heat-sink structure requirements are reduced.

The design and construction of the 294H components were selected to maximize efficiency and operating life

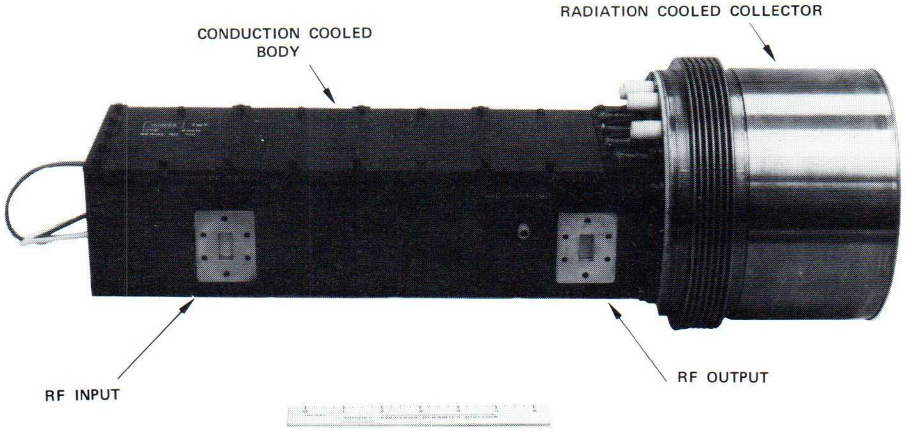


Figure 7. 294H 100-watt 12-GHz space TWT

while minimizing weight and baseplate heat dissipation. Extensive computer analyses were performed on the electron gun, PPM focusing system coupled-cavity circuit, and multistage depressed collector in order to establish the optimum configurations.

High efficiency circuit design. The coupled-cavity slow-wave structure for the 294H is comprised of three internally-terminated sections for stable operation with 45 to 50 dB of gain. A velocity taper was included by reducing the cavity period in two discrete steps at the circuit output in order to obtain the highest basic (undepressed) efficiency. This efficiency then determines the beam power necessary to produce the desired RF output power. The selection of the circuit design requires complex trade-offs between operating voltage, efficiency and beam focusing constraints. In coupled-cavity TWT's with 100 to 1000 watts output power, the basic interaction efficiency increases for lower beam voltage, higher beam current designs. However, lowering the operating voltage increases the magnetic focusing field required for good beam transmission while the smaller circuit period needed for a lower voltage design reduces the available magnetic field. For the 294H the focusing limitation dictated an operating voltage of 8 kilovolts.

The single-most important factor limiting the basic efficiency of any traveling-wave tube is the loss of synchronism between the RF wave propagating along the slow-wave structure and the electron beam. Synchronism is necessary to transfer kinetic energy from the electrons in the beam to amplify the RF wave. At tube saturation the power extraction from the beam is so large that its average velocity (kinetic energy) is no longer greater than the phase velocity of the RF wave, and the energy exchange ceases. This effect is depicted in the upper curve of Figure 8. Maintaining synchronism of the RF wave phase velocity and the average electron beam velocity at large modulation levels over a longer distance greatly increase the efficiency of the TWT. The step velocity taper technique achieves this effect by reducing the phase veloccity of the RF wave at the same rate as the average beam velocity.

In a high efficiency velocity taper tube such as the 294H, the first two sections are operated near synchronism rather than over-voltaged. The RF power level is low, but very favorable beam modulation results at the beginning of the taper. A strong interaction then takes place, with the RF power increasing to a second maximum (saturation). This point determines the optimum length of the taper section. Figure 8 illustrates the efficiency as a function of circuit length for both a conventional TWT and the 294H. The first saturation at the beginning of the taper has a lower efficiency than the maximum efficiency (typically 12 to 14%) of the conventional tube, but the ultimate efficiency at the end of the taper section is nearly twice as high (25 to 28%).

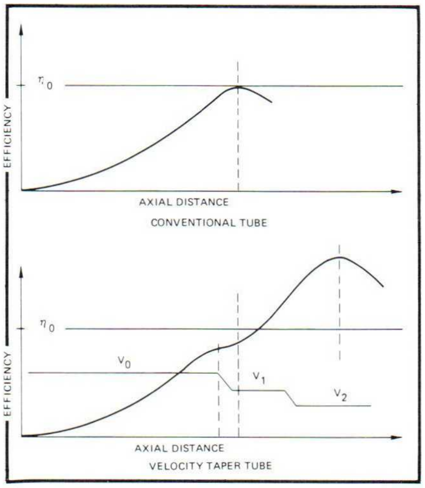


Figure 8. Velocity taper efficiency enhancement

The important design parameters for the taper are the magnitude of the velocity steps, the taper lengths, and the total output section length. All these parameters are dependent on other beam and circuit characteristics and each is analyzed individually. The final design was established after extensive large signal interaction computer analysis. The analysis was accurate to within one percentage point of measured 294H performance.

294H Focusing Considerations. Electron beam focusing is also an important factor in the performance and reliability of the 294H TWT. Beam current interception on the RF slow-wave structure determines, to a large extent, the internal tube operating temperatures and baseplate heat dissipation. Such intercepted current also degrades the overall TWT efficiency, since it is collected at its full potential energy, possibly before it can interact with the RF wave.

The coupled-cavity structure provides an excellent magnetic circuit for PPM focusing of the beam. The cavity walls are fabricated of soft iron for use as magnetic pole pieces. The focusing magnets are situated between adjacent pole pieces and outside the copper spacers which form the outer diameter of the cavities. The effective focusing field is generated in the ferrule gaps, in close proximity to the beam. Double-period focusing is used in the 294H to produce the necessary magnetic field with minimum magnet weight. The double-period structure and resulting axial magnetic field are shown in Figure 9.

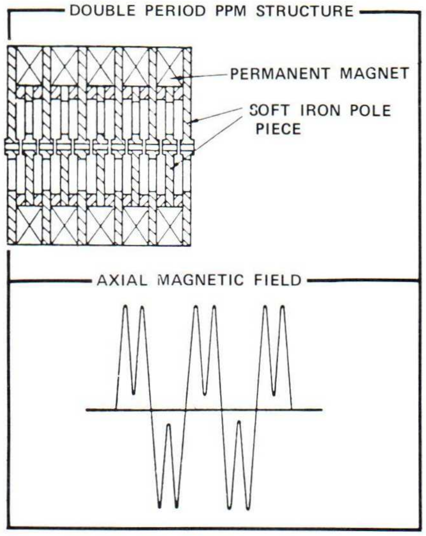


Figure 9. Double PPM focusing structure and axial magnetic field

A Pierce type, convergent electron gun is used to generate the electron beam in this tube. A barium-impregnated tungsten matrix cathode and an alumina-potted heater assembly are used to assure reliable operation over 30,000 hours at a cathode current density of 0.5 A/cm^2. Oxide cathodes are not used in high power TWT's because they cannot produce the relatively high current densities required. The design of the gun was determined by computer analysis which included the effects of the electron thermal velocities and the PPM fringing fields.

The Multi-Stage Collector. The radiation-cooled, three-stage depressed collector is one of the most important components of the 294H. The collector has three electrical functions: (1) to sort electrons in the modulated beam by velocity; (2) to slow the electrons and collect them at the lowest possible kinetic energy and thereby minimize heat dissipation and maximize overall TWT efficiency; and (3) to prevent back streaming of electrons, both reflected primaries and secondaries, into the slow-wave circuit. The determination of the correct collector electrode geometries and depression voltages, which are dependent on the trajectories and kinetic energies of the electrons in the modulated beam, is accomplished by computer calculations of the trajectories within the collector. Iterative changes are made to the collector until maximum efficiency is achieved.

A cross-section drawing of the 294H collector is shown in Figure 10. The electrons are intercepted on the surface of each electrode facing away from the tube. In this way, secondaries are effectively suppressed by the decelerating voltage gradient.

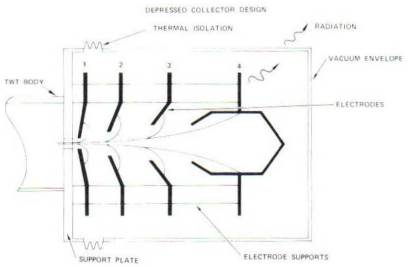


Figure 10. Cross section of 4-stage depressed collector for 294H

The four collector elements are electrically and thermally insulated from each other, the TWT body, and the vacuum envelope. The insulators also provide mechanical support for the electrodes. Heat is dissipated by radiation to the other electrodes, to the vacuum envelope, and then to deep space. The element temperatures are strongly influenced by the RF output power. This is because the distribution of current to the electrodes is determined by the beam energy spread which, in turn, is a function of the RF output power. With no RF drive the total collector dissipation is 127 watts and the molybdenum element temperatures vary from 250°C to 400°C. Less than 10% of the heat dissipation in the collector is transferred to the tube body. This is accomplished by using a thermal choke at the base of the vacuum envelope and radiation heat shields between the first collector element and the tube body. The collector is cantilevered from the output end of the tube's baseplate. The diameter of the elements and envelope were minimized consistent with a 400°C maximum internal temperature.

Package Design. The TWT package performs three functions. It maintains rigid support and accurate alignment of the collector and RF circuit. It also provides conduction cooling for the RF circuit and evenly distributes the dissipated heat along the baseplate. The heat flux density is about 5 watts per square inch with a maximum baseplate dissipation of 56 watts. Finally, the package supports the cantilevered collector and distributes this load over the length of the TWT baseplate. Fully packaged, the 294H weighs less than 20 pounds and meets the shock and vibration of the Thor-Delta launch vehicle.

Table II
294H Operating Parameters

Power Out	129 W
Gain	46 dB
Basic Efficiency	27%
Overall Efficiency	52%
Cathode Voltage	−8.00 KV
Cathode Current	59 MA
Transmission	95%
Filament Power	5 W

Collector	Voltage (KV)	Current (P_o=O) (MA)	Current (P_o=129 W) (MA)
1	0	0.4	1.0
2	−2.75	1.3	13.2
3	−3.45	1.5	21.6
4	−6.00	55.4	19.9

Tube Performance. Typical operating parameters for the 294H at saturation are listed in Table II. Under these conditions, it is producing 129 watts with an undepressed (basic) efficiency of 27%. The three-stage collector increases that efficiency to 52 percent. Another indication of the effectiveness of this collector is that with no RF drive applied, nearly all of the beam is collected on the last electrode, operating at only 25 percent of cathode voltage. This greatly reduces the prime power and heat dissipation for small signal operation.

Typical output power of the 294H at saturation over the 180-MHz frequency band from 11.95 to 12.13 GHz is 120 watts minimum with a total amplitude variation of less than 0.5 dB. Within any 50-MHz band the amplitude varies less than 0.2 dB. Across the same 180 MHz band the tube's overall efficiency is greater than 50%, reaching 52% at midband. Looking at the phase linearity at saturation from 11.95 to 12.13 GHz, deviation from linear is less than 6.5 degrees in any 50-MHz band. No external equalization was required to achieve this performance.

Signal transmission tests using actual color TV signals have been successfully performed using a 294H in a simulated satellite transponder.

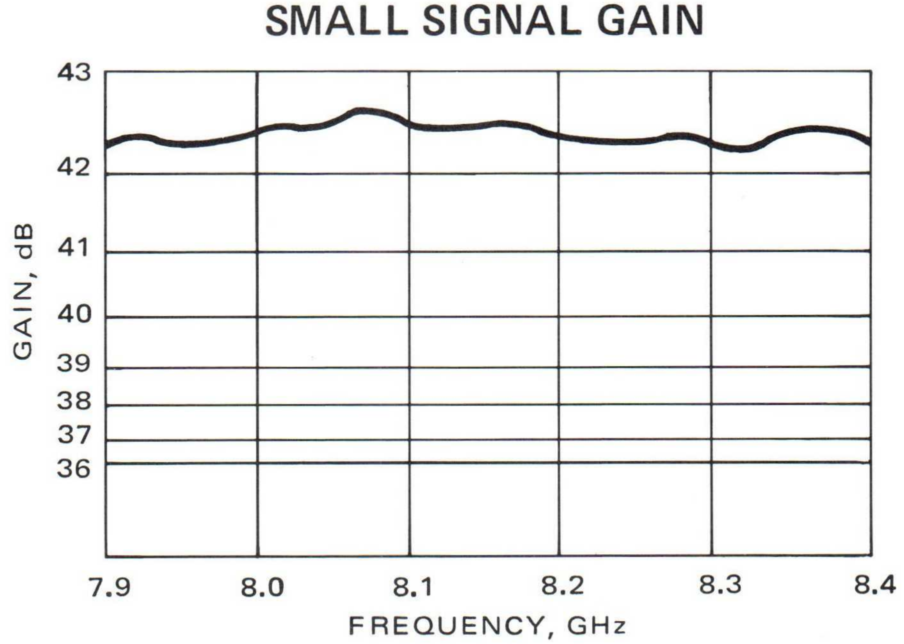
Conclusion. These two coupled-cavity TWT's are good examples of the present state of the art in high power communications amplifiers. The techniques utilized to achieve low signal distortion, high efficiency, broad bandwidth and simplified cooling interface requirements are applicable to a wide range of power levels and frequencies that may be encountered in communications system applications.

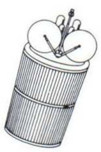
In the future, coupled-cavity traveling-wave tube developments will result in CW communications amplifiers at frequencies up to 100 GHz and increased output power levels. High efficiency resynchronization and multistage collector depression techniques will be applied to many more TWT designs to save energy and minimize cooling requirements. TWT efficiencies will continue to be increased to levels that in the past could only be achieved by narrow band klystron amplifiers. The use of multi-stage collectors will be particularly effective in tubes for multicarrier amplification where operation at reduced output power levels (and, hence, reduced basic efficiency) is necessary for low intermodulation products. Efficiencies of 25% or greater are achievable objectives.

The recent developments in high energy rare-earth magnetic materials and heat pipe technology have made possible PPM-focused, air-cooled, coupled-cavity TWT's producing greater than one kilowatt of RF output power in the I and J bands. Such tubes can put inexpensive, transportable ground terminals within reach.

Further reductions in high power TWT amplitude and phase variations with frequency will be achieved as the matching and equalization techniques are refined. Methods of linearizing the tube input/output transfer characteristic to permit reduction of intermodulation products near saturation are also being investigated. These developments will continue to improve the performance characteristics of high power coupled-cavity TWT's and the communications systems in which they are used. ■

The truth about Hughes communications TWTs. With a minimum of distortion.





Performance of a typical Hughes TWT: Model 792H TWT achieves a minimum distortion level of just 0.5 dB from 7.9 GHz to 8.4 GHz.

Hughes high-power communications TWTs have a patented circuit designed to achieve minimum phase variation and maximum gain flatness.

Model 792H is a 5 kW CW X-Band TWT for ground terminals. It provides continuous RF power over a frequency range of 7.9 to 8.4 GHz and is also available in 3 or 8 kW models.

And, for earth orbiting satellites, Hughes has developed Model 294H, 100 and 200 watt TWTs at 12 GHz. These lightweight TWTs achieve a remarkable 50% efficiency.

To get the undistorted truth about these and other communications TWTs, write: Hughes Electron Dynamics Division, 3100 West Lomita Blvd., Torrance, Calif. 90509. Or call (213) 534-2121, extension 223.

HUGHES

HUGHES AIRCRAFT COMPANY
ELECTRON DYNAMICS DIVISION

For High-Power Protection ... Try Multipacting

Fast recovery radar receiver protection can be effectively accomplished by exploiting the principle of multipacting. Recovery times of five to 50 nanoseconds are possible.

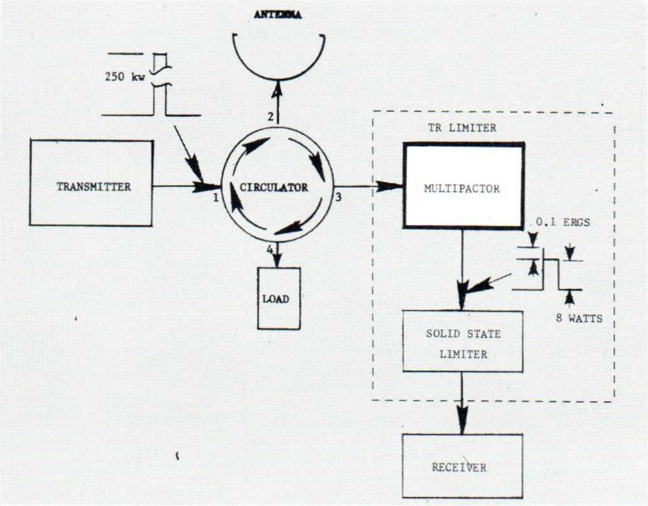
Transmit-receive (TR) limiters serve two basic functions. Firstly, they attenuate power entering the receiver during a transmitted pulse to a level which will not harm the receiver or bias it to a temporarily insensitive condition. Secondly, during receiver on-time, the limiter provides a path of minimum insertion loss, subjecting the receiver to the strongest possible return signal.

Over the last several years, a number of high PRF radar systems have evolved which require a TR limiter system that can handle powers on the order of hundreds of kilowatts, yet display insertion losses of about 0.5 dB and recovery times of less than 50 nanoseconds. This very short recovery time is a second requirement for monitoring the maximum possible return signal. Taking advantage of the principle of multipacting (multiple impacting) is one way to meet these demanding specifications.

Figure 1 shows the relative location of a multipactor TR limiter system in a simplified radar block diagram. The protective circuit consists of a high-power stage (multipactor) which limits the power to several watts, and a low power stage (solid-state limiter) which further reduces the power to milliwatts.

Basically, the multipactor section offers protection against three potentially dangerous situations. When the transmitter is on, up to 10% of the transmitted power (250 kW peak) can be reflected due to the impedance mismatch of the antenna. Thus, the multipactor is normally required to limit approximately 25 kW of reflected power to about 8 watts. A more serious limiting problem can occur during transmitter on-time if a high-power arc should develop at the antenna. In this case, up to 80% reflection can occur and the multipactor section must attenuate approximately 200 kW down to 8 watts. In both cases, the limited power is absorbed by the multipacting process and the resulting heat is removed by conduction cooling.

A third limiting process occurs when extraneous radar signals are present. The rf circuit of the multipactor essentially constitutes a bandpass filter. Since the operating band of the multipactor is coincidental with the passband, any out-of-band signals received by the antenna will be reflected and absorbed as port No. 4 of the circulator by the dummy load. The multipactor section of the limiter requires no synchronous signal for operation. The first half cycle of the incident rf wave initiates the multipacting process.



1. **Two-stage multipactor** limiters handle up to 250 kW peak power at X-band.

The physics of multipacting

Multipacting can occur in most low pressure environments in the presence of moderate to high levels of rf energy. The impact of high-energy electrons upon a solid surface causes the emission of secondary electrons of much lower energy. These secondaries then impact on other surfaces to produce more secondaries. This process is called multiple impacting. In most instances, the effect is undesirable and some effort is required to passivate the incident surface in order to inhibit multipacting. However, secondary emission can be taken advantage of in high-power limiters.

The basic multipactor geometry is shown in Figure 2. The surfaces bounding the gap are prepared and coated with a high yield secondary emission material (SEM) such as magnesium oxide (MgO). A small, noncritical electron gun (not shown) insures

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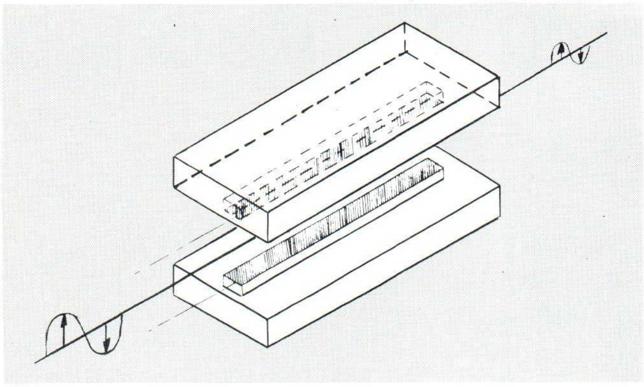
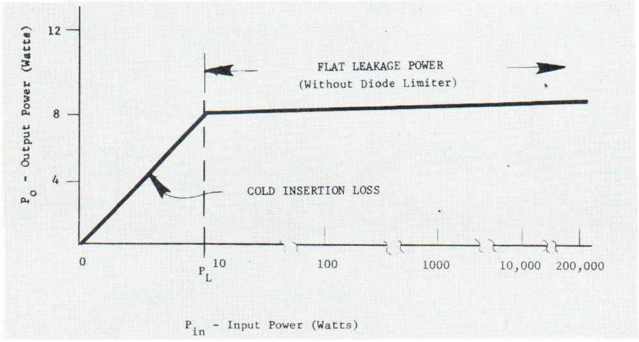
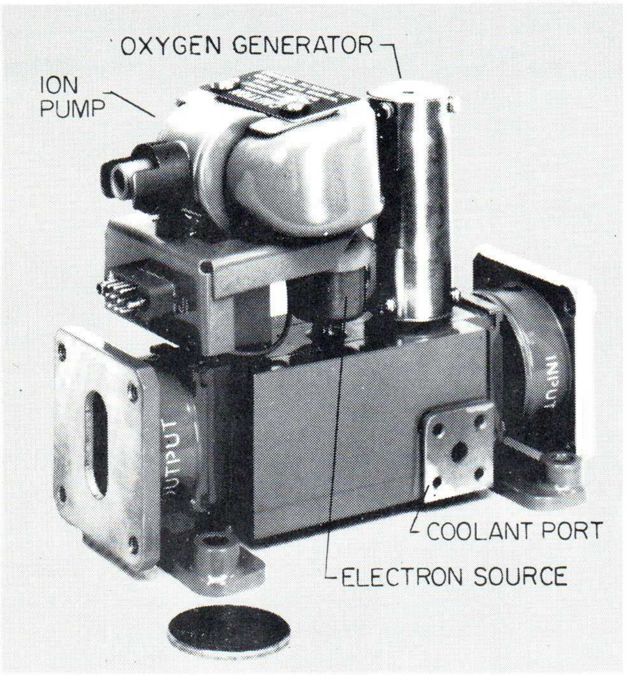


2. **A secondary emission material** such as MgO is deposited onto opposing flat surfaces. The gap between the two surfaces governs the threshold power.



3. **Below threshold power (P_L),** the insertion loss is minimal. After the onset of multipacting, however, input power is limited at about 8 watts.



4. **Actually a small system,** the multipactor limiter requires electron and oxygen sources as well as an ion pump.

that there are some free electrons in the gap at all times. The electric field generated by the incoming rf wave, forces electrons to traverse the gap and impinge upon the coated surface. When each of these electrons collide with the SEM, 10 to 15 secondary electrons are released. As the electric field changes polarity during the next half cycle, the emitted electrons are accelerated across the gap and strike the opposing surface. If the transit time of the electrons across the gap is one-half cycle of the rf field, large electron densities will rapidly build up in the gap.

The number of electrons in the gap continue to increase until space charge forces oppose the accelerating force of the rf electric field. Thus, new secondary electrons see a large space charge field which prevents them from joining the multipacting electron cloud. The final state of equilibrium exists when only one secondary electron joins the cloud for every impinging electron on the secondary surface. The electron cloud moves in phase with the applied oscillation electric field, and consequently, energy is absorbed from the rf field. All but a small fraction of the incoming rf power is dissipated thermally at the SEM surfaces. The power not absorbed is transmitted as "flat leakage power."

The theory[2] of multipacting is based on the one-dimensional equation of motion for a free electron subjected to the electric field of an rf wave. Applying the boundary condition that the electrons require an odd number of half cycles or rf voltage to traverse the gap, the synchronous voltage required is

$$V_o = \frac{4\pi d^2 f^2}{\eta}$$

where $d =$ resonator gap
$f =$ frequency of the incoming wave
$\eta =$ electron charge-mass ratio

Using this relation, the input power level (P_L) required for the onset of multipacting, i.e., limiting, (Fig. 3) is

$$P_L = \frac{8\epsilon_0 W v_g d^3 f^4}{\eta^2}$$

where $\epsilon_0 =$ permittivity of free space
$W =$ width of ridge
$v_g =$ phase velocity of the rf wave

For example, consider the conditions where $f = 10$ GHz, $d = 9$ mils, $P_L = 5$ watts. For an increase in gap distance of 1.0 mils, the threshold power will increase to 6.85 watts. Obviously, the resonator gap must be maintained to close tolerances.

An external view of a multipactor limiter system is shown in Figure 4. The multipactor structure is built in waveguide. The main body of the multipactor is an all-brazed copper structure. The free electrons required for multipacting are supplied by the electron source. During multipacting, the magnesium oxide SEM is reduced to magnesium, its base-metal state. The oxygen required to reoxidize the SEM is provided by an internal oxygen generator. An ion pump provides the proper vacuum for multipacting operation. ●●

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