

Applying Coaxial Transmission Line Rating To Various Broadcasting Services

The following information must be identified to select a suitable rigid coaxial transmission line:

- A. Operating frequency
- B. Modulation scheme
- C. Maximum average power required
- D. Maximum peak power required
- E. Environmental extremes

Critical Frequencies of Transmission Line, Selecting a Transmission Line Length

All rigid coaxial connectors exhibit a minor deviation from the characteristic impedance of the transmission line. This deviation causes a minute amount of power to be reflected back towards the transmitter and is known as Voltage Standing Wave Ratio (VSWR). A transmission line system, utilizing a correct fixed line length, will exhibit a VSWR buildup that occurs outside the broadcast band of operation. The following equation identifies these critical frequencies:

$$F_c = \frac{490.4}{L_{ft}} n$$

F_c = Critical Frequency
 L_{ft} = Line Length in Feet
 n = An Integer

The response is a distribution similar to a band stop filter, repeating at each critical frequency. Critical frequencies must be kept at a minimum of 2 MHz away from any operating frequency. Rigid air coaxial transmission lines are normally supplied in standard lengths of 20', 19 3/4', 19 1/2', 19', and 17 1/2' to accommodate the broadcasters needs. Selection of the proper line length for a given frequency will insure a transmission line system with low VSWR. The table below is used to find the correct line length for United States television and FM radio channel assignments.

TV Channels requiring 20' line sections										
2	3	4	5	6	7	8	11	12	14	15
18	19	22	23	27	31	35	39	43	44	47
48	51	52	55	56	60	64	68			
TV Channels requiring 19 3/4' line sections										
16	20	24	28	32	36	40	41	45	49	53
57	61	65	66	69						
TV Channels requiring 19 1/2' line sections										
9	10	13	17	21	25	26	29	30	33	34
37	38	42	46	50	54	58	59	62	63	67
FM frequencies requiring 20' line sections										
88.1 through 95.9 MHz and 100.1 through 107.9 MHz										
FM frequencies requiring 19' line sections										
96.1 through 99.9 MHz										
All FM frequencies can be use on 17 1/2' line sections										

The table that follows shows the critical frequencies for the standard line lengths in the frequency range for U.S. broadcasting. Approximately 75% of any combined two channel application can be accommodated with a standard line length.

Critical Frequencies of Transmission Lines in MHz.					
N	20.00'	19.75'	19.50'	19.00'	17.50'
1	24.52	24.83	25.15	25.81	28.02
2	49.04	49.66	50.30	51.62	56.05
3	73.56	74.49	75.45	77.43	84.07
4	98.08	99.32	100.59	103.24	112.09
5	122.60	124.15	125.74	129.05	140.11
6	147.12	148.98	150.89	154.86	168.14
7	171.64	173.81	176.04	180.67	196.16
8	196.16	198.64	201.19	206.48	224.18
9	220.68	223.47	226.34	232.29	252.21
10	245.20	248.30	251.49	258.11	280.23
11	269.72	273.13	276.64	283.92	308.25
12	294.24	297.96	301.78	309.73	336.27
13	318.76	322.79	326.93	335.54	364.30
14	343.28	347.63	352.08	361.35	392.32
15	367.80	372.46	377.23	387.16	420.34
16	392.32	397.29	402.38	412.97	448.37
17	416.84	422.12	427.53	438.78	476.39
18	441.36	446.95	452.68	464.59	504.41
19	465.88	471.78	477.83	490.40	532.43
20	490.40	496.61	502.97	516.21	560.46
21	514.92	521.44	528.12	542.02	588.48
22	539.44	546.27	553.27	567.83	616.50
23	563.96	571.10	578.42	593.64	644.53
24	588.48	595.93	603.57	619.45	672.55
25	613.00	620.76	628.72	645.26	700.57
26	637.52	645.59	653.87	671.07	728.59
27	662.04	670.42	679.02	696.88	756.62
28	686.56	695.25	704.16	722.69	784.64
29	711.08	720.08	729.31	748.51	812.66
30	735.60	744.91	754.46	774.32	840.69
31	760.12	769.74	779.61	800.13	868.71
32	784.64	794.57	804.76	825.94	896.73
33	809.16	819.40	829.91	851.75	924.75
34	833.68	844.23	855.06	877.56	952.78

When multiple channels are to be used on a single transmission line, and a standard line length is not suitable for the application, then a non-standard length line can be utilized for the application. MYAT uses a computer algorithm to determine the best line length for any number and combination of channels.

Broad Band Rigid Coaxial Transmission Line

When the application frequency is subject to be moved to an unknown channel allocation, as is the case for some U.S. broadcasters who were allocated a channel outside the core spectrum, a Broad Band Rigid Coaxial Transmission Line should be considered.

MYAT engineers have developed patented computer algorithms, which determine the optimum dimensions for each line section and component in your site configuration. Only MYAT's design algorithms include horizontal run, elbows, elbow complexes, vertical run, and typical expected field cuts. The result is high power handling capability, minimum VSWR, and the industries highest efficiency across the entire NTSC and DTV UHF band. The **SPECTRALINE™** system you install today will continue to perform equally well even if a channel change becomes necessary in the future. Please refer to our **SPECTRALINE™** information section for further information.

Selecting the Correct Line Size

All services that will be utilizing the transmission line system must be considered when selecting a suitable line size. The total length of a transmission line run, from transmitter output to antenna input, is needed to estimate the attenuation of each signal, and, as a result, the power delivered to the load or antenna. Larger diameter transmission lines have lower attenuation, higher average power, and higher peak power ratings. For a given line size, a 75 ohm characteristic impedance has lower attenuation and lower power handling than a 50 ohm characteristic impedance. Selecting the largest line size available for an application will minimize operating costs.

The principle mode of propagation for coaxial transmission lines is TEM (Transverse-Electro-Magnetic). Both electric and magnetic fields are perpendicular to the direction of propagation. This mode is the most efficient for coaxial lines. Each line size has a cut-off frequency above which the principle mode of propagation (TEM) will no longer transfer energy efficiently, due to a higher order "waveguide" mode disrupting the transmission characteristics. Larger diameter transmission lines have lower cut-off frequencies. The theoretical cut-off frequency is calculated using the formula below and adjusted to a useful cut-off frequency limit, accounting for elbows normally present, to a point where other modes of propagation do not occur. When selecting a coaxial line size, all frequencies must be below the useful cut-off frequency for systems that normally include elbows and elbow complexes. It should be understood that a system that is comprised of only straight-line sections could achieve up to 95% of the theoretical cut-off frequency.

$$F_{Cut-off} = \frac{7500}{\sqrt{E}(D + d)}$$

$F_{Cut-off}$ = Theoretical Cut-off Frequency

E = Insulation Dielectric Constant, Air = 1.0006

D = I.D. of Outer Conductor

d = O.D. of Inner Conductor

Line Size	Calculated Cut-off, MHz	Useful, Cut-off MHz	Outer I.D. (in)	Inner O.D. (in)
7/8" 50 ohm	6658.749	6000	0.785	0.341
1 5/8" 50 ohm	3422.068	3000	1.527	0.664
3 1/8" 50 ohm	1726.797	1600	3.027	1.315
4 1/16" 50 ohm	1327.976	1262	3.935	1.711
6 1/8" 50 ohm	873.762	806	5.981	2.600
6 1/8" 75 ohm	974.747	830	5.981	1.711
7 3/16" 75 ohm	833.083	752	7.000	2.000
8 3/16" 75 ohm	728.644	704	8.000	2.290
9 3/16" 50 ohm	580.771	552	9.000	3.910
9 3/16" 75 ohm	647.474	615	9.000	2.580

Average Power Considerations

The weighted average power is defined as the average power, plus reflected power from the highest expected VSWR. The highest expected VSWR is used as a margin of safety to account for system accumulation, (source, line, and load), and unforeseen problems, such as increased VSWR due to ice forming on an antenna. The weighted average power value is then used to estimate the heat rise of the inner conductor for each service. All MYAT rigid air coaxial transmission lines are designed and rated for an ambient temperature of 40°C (104°F) and limiting the inner conductor to 100°C (212°F). The formula below is used to estimate the heat rise of the inner conductor for the average power of each service. The sum of all heat rises must not exceed 60°C, (highest ambient of 40°C + maximum heat rise of 60°C = 100°C limit for the inner conductor), for a reliable long-term system service life to be realized for MYAT standard transmission line designs.

For Amplitude Modulation (AM), the peak power rating of a coaxial transmission line is the limiting factor.

$$H_{RISE} = \frac{P_{AVE_SERVICE}}{P_{AVE@RATING_FREQ}} 60^{\circ}C$$

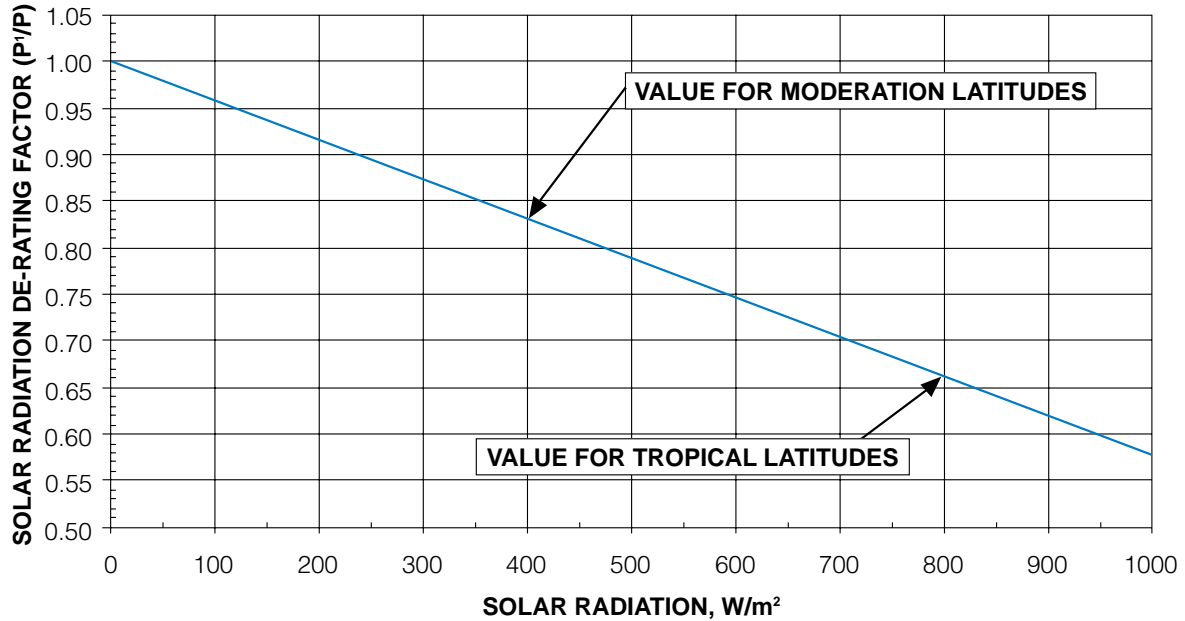
H_{RISE} = Heat Rise Due To One Applied Service, (°C)
 $P_{AVE_SERVICE}$ = Weighted Average Power For One Service
 $P_{AVE@RATING_FREQ}$ = Power Rating Limit At Service Frequency

The standard average power rating, and the standard transmission line design, can be used at other than the 40°C highest ambient temperature rating. No special considerations, or higher power handling designs, are required, provided the standard average power rating is not exceeded. Observing the rating limit insures an inner conductor heat rise no greater than 60°C above the highest ambient temperature with a proper use of the transmission line design for differential expansion between the inner and outer conductors. MYAT's standard transmission line designs and ratings will provide for reliable long-term service for a vast majority of broadcast applications.

De-rating Average Power for Solar Radiation

Solar radiation plays an important roll in applying the average power rating. Radiant energy from the sun will add to the heat buildup of a coaxial transmission line. When the exterior surface of a copper coaxial transmission line is bright, heat conduction by radiation is poor. When the copper becomes oxidized over time, heat conduction by radiation is greater. The emissivity value from bright to oxidized copper changes from approximately 0.03 to 0.8 respectively. The de-rating factor on the chart below is for solar radiation and is applied where direct sunlight is perpendicular to the transmission line in its oxidized state. The solar radiation value, for de-rating purposes, should be the mean solar radiation at the angle of incidence for the site of application. For the United States, this information can be obtained from the National Meteorological Center. Oxidation of copper in an outdoor environment cannot be avoided. Applying a special coating can improve the emissivity value to approximately 0.95, and minimize solar absorption to 0.3, but should only be considered when there is no alternative. In addition, relying on a coated surface for power handling ability results in a coating maintenance issue dependant on the atmospheric condition at the site of installation. Both MYAT standard and custom engineered transmission line systems can be supplied with MYAT **Solar Coat™**, which increases the transmission line dissipation of heat while minimizing solar absorption. This coating can yield an average power rating gain of 28% for 50 ohm lines and 23% for 75 ohm lines.

Average Power De-Rating Factor For Solar Radiation



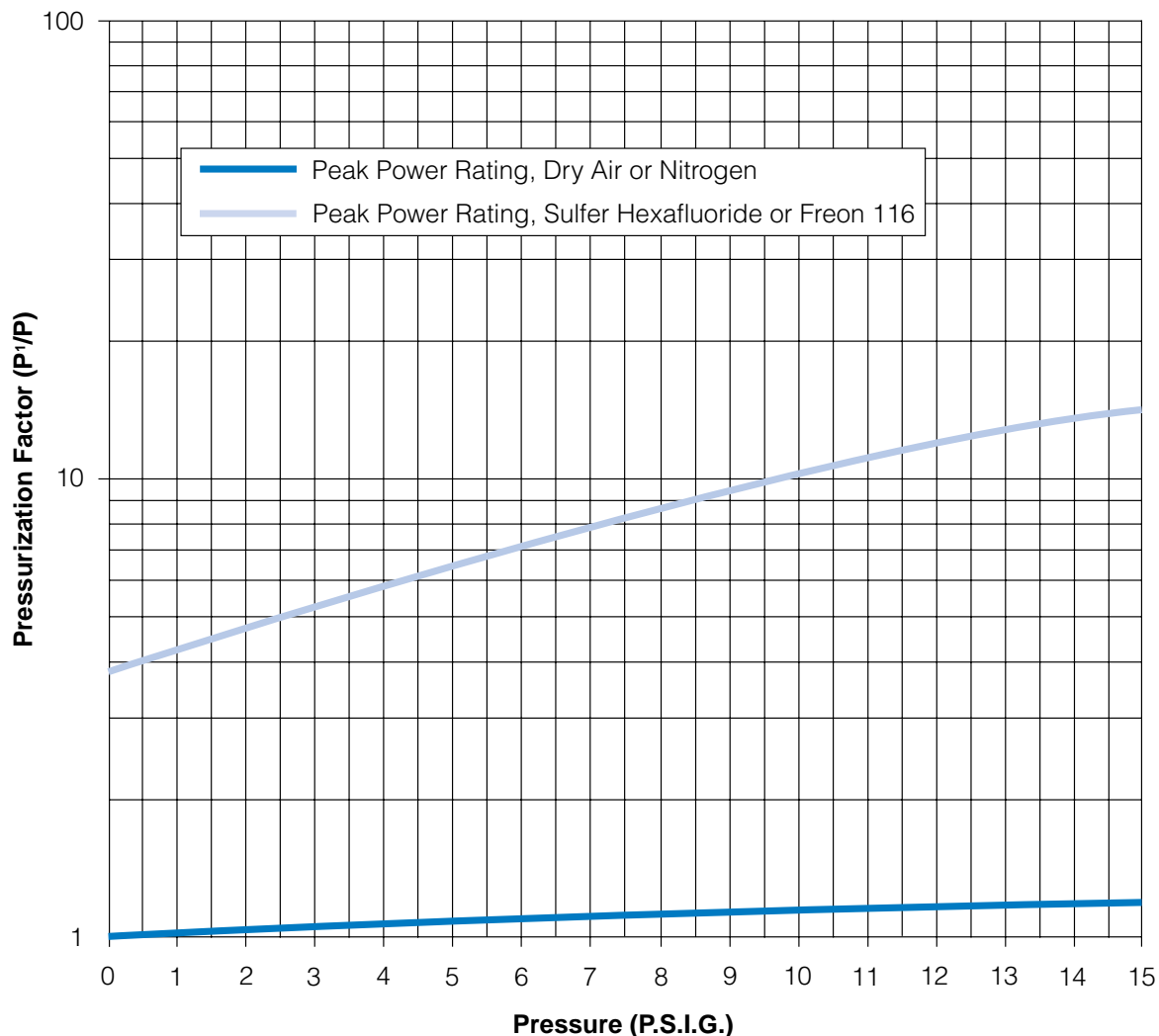
Pressurization of Transmission Line

All rigid coaxial transmission line systems must be maintained with a positive pressure of dry air, or nitrogen, at all times. This positive pressure will help insure that the line is kept clean and dry, and help prevent moisture from entering the system. Moisture in the line will increase VSWR and attenuation, and result in poor line performance and degradation of signal quality. Moisture and/or water in the line can also cause voltage breakdown resulting in catastrophic failure. MYAT recommends that a minimum of 2 PSIG to 5 PSIG of dry air or nitrogen be continually maintained in the line system. Pressurization can also be used as a device to improve the average power, and peak power rating of a transmission line. The table below lists improvements in average power rating versus pressure.

Average Power Rating Gain Due To Pressurization		
Pressure (P.S.I.G.)	P'/P Factor for 50 Ohm Line	P'/P Factor for 75 Ohm Line
0	1.00	1.00
5	1.09	1.08
10	1.16	1.15
15	1.21	1.22

Peak power ratings for rigid line can also be improved by increasing air pressure. Additionally, by using a gas with a higher dielectric coefficient than dry air or nitrogen, such as sulfur hexafluoride, further gains can be made in increased peak power capacity. The chart below demonstrates the effects of increased pressure on peak power capacity.

Peak Power Rating Gain By Pressurization



Each broadcasting service, AM, FM, NTSC Television, and DTV, has different requirements for estimating the peak and average power that will be present on a transmission line. When multiple services will be present on a coaxial transmission line, the sum of the peak power for each service should be less than or equal to the peak power rating of the selected coaxial transmission line size, and the sum of the heat rise due to the average power for each service, should not exceed 60°C. The equations below are organized to consider the peak and average power for each broadcast service requirement.

De-Rating Peak and Average Power for VSWR

MYAT recommends de-rating the peak and average power ratings to account for the highest expected VSWR the system may encounter. De-rate by dividing the rating directly by the estimated worst-case VSWR. This conservative approach insures long-term service life and reliability.

AM Service

For an amplitude-modulated service, (530-1610kHz), coaxial transmission lines are limited by the peak power rating. The following equation is used for estimating the peak power requirement for an amplitude-modulated service. From this equation it can be seen that 100% modulation increases the peak power requirement by a factor of 4; also, the peak power in a transmission line increases directly with VSWR. It is common to consider a total system VSWR of 3.0 for an AM service.

$$P_{PEAK} = P_T (1 + M^2) VSWR$$

P_{PEAK} = Peak Power Requirement (kW)

P_T = Transmission Power (kW)

M = Amplitude Modulation (decimal percentage: 100%=1.0)

$VSWR$ = Expected total system Voltage Standing Wave Ratio

FM Service

For a frequency-modulated service, (88-108MHz), coaxial transmission lines are limited by the average power rating. The transmitter average power rating, or maximum average power that will be present at the output of the transmitter, should be used in selecting a coaxial transmission line size. The peak power that will be present will always be less than the lines peak power rating. The peak power can be calculated using the equation below.

$$P_{PEAK} = 1.414 \sqrt{P_T Z_O}$$

P_{PEAK} = Peak Power Requirement (kW)

P_T = Transmission Power (kW)

Z_O = Characteristic Impedance

NTSC Television Service

NTSC television transmitter ratings are based on sync peak video power. The maximum peak sync video power of the transmitter that will be applied should be used in selecting a transmission line, or when multiple services are to be combined in one line. The maximum average power for the application is equivalent to 60% of the sync peak video power for visual signal, plus 10% to 20% of the sync peak video power to account for the aural signal.

$$P_{AVE_VISUAL} = 0.6 P_{PEAK_SYNC_VIDEO}$$

$$P_{AVE_AURAL} = K_{AURAL} P_{PEAK_SYNC_VIDEO}$$

$$P_{AVE_TOTAL} = P_{AVE_VISUAL} + P_{AVE_AURAL}$$

$$V_{P_VISUAL} = 1.414 \sqrt{P_{PEAK_SYNC_VIDEO} Z_O}$$

$$V_{P_AURAL} = 1.414 \sqrt{P_{AVE_AURAL} Z_O}$$

$$V_{P_TOTAL} = V_{P_VISUAL} + V_{P_AURAL}$$

$$P_{PEAK_EQUIVALENT} = \frac{V_{P_TOTAL}^2}{Z_O}$$

P_{AVE_VISUAL} = Visual Average Power (kW)

P_{AVE_AURAL} = Aural Average Power (kW)

K_{AURAL} = Percentage Aural (10%=0.1, 15%=0.15)

$P_{PEAK_SYNC_VIDEO}$ = Peak Sync Video Power (kW)

V_{P_VISUAL} = Visual Peak Voltage

V_{P_AURAL} = Aural Peak Voltage

V_{P_TOTAL} = Total Peak Voltage

Z_O = Characteristic Impedance

$P_{PEAK_EQUIVALENT}$ = Equivalent Peak Power (kW)

DTV, Digital Television Service

The digital television service approved by the FCC for the United States uses an 8-VSB, (Eight Vestigial Side Band), modulation scheme. The peak power requirement for the transmission line is four to five times the average power requirement and is directly related to the model of transmitter to be used. Both peak and average power ratings should be considered when selecting a transmission line for DTV, or when combining with other services. The equation below is used for estimating the transmission line requirements for DTV.

$$P_{AVE_DTV} = \frac{P_{PEAK_DTV}}{R_{TRANSMITTER}} \quad \begin{array}{l} P_{PEAK_DTV} = \text{Transmitter Peak Power Output or System Requirement (kW)} \\ R_{TRANSMITTER} = \text{Peak to Average Power Ratio of Transmitter, (5 if unknown)} \end{array}$$

Multiple Service Guidelines

When combining multiple services, be sure that the sum of heat rise, due to the average power of each service, does not exceed the transmission line rating or the adjusted rating for that application. Additionally, be sure the equivalent peak power for the combined services does not exceed the transmission line rating, or the adjusted rating for application. Below is an example for combining a DTV service with a NTSC service.

$$H_{RISE_TOTAL_AVE_NTSC_POWER} + H_{RISE_AVE_DTV_POWER} = H_{RISE_TOTAL}$$

$$V_{PEAK_NTSC_VISUAL} + V_{PEAK_NTSC_AURAL} + V_{PEAK_DTV} = V_{PEAK_TOTAL}$$

$$Equivalent_Peak_Power = \frac{V_{PEAK_TOTAL}^2}{Z_0}$$

Planning and Installation Requirements

The tables below must be used to accommodate the differential of expansion and contraction between a broadcast tower and the transmission line. A minimum horizontal run length is required to minimize the stress on the elbow at the base of the tower. The distance between the tower base to the transmitter building should be planned to accommodate the largest horizontal run requirement for the tower height and the largest transmission line size and type to be installed. The minimum distance to the first vertical hanger is required to permit expansion and contraction of the horizontal run to minimize the stress on the elbow at the base of the tower.

Minimum Horizontal Run Length vs. Vertical Run Length						
Line Size / Vertical Run	3 1/8"	4 1/16"	6 1/8"	7 3/16"	8 3/16"	9 3/16"
250'	18'	20'	24'	26'	28'	30'
500'	20'	28'	34'	37'	39'	40'
750'	30'	33'	41'	43'	46'	50'
1000'	40'	38'	48'	51'	54'	60'
1500'	45'	50'	60'	64'	67'	70'
2000'	50'	60'	68'	72'	77'	80'

Minimum Vertical Distance to First Vertical Spring Hanger Above Horizontal Run							
Horizontal Run / Line Size	20'	30'	40'	50'	60'	70'	80'
3 1/8"	5.5'	6'	7'	8'	-	-	-
4 1/16"	7'	9.5'	11'	12.5'	14'	-	-
6 1/8"	8'	10.5'	13'	14.5'	16'	17'	-
7 3/16"	10'	12.5'	15'	16.5'	18'	19'	20'
8 3/16"	10'	12.5'	15'	16.5'	18'	19'	20'
9 3/16"	10'	12.5'	15'	16.5'	18'	19'	20'

Install the first vertical spring hanger the recommended distance above the base elbow so that the first section of line can move as the horizontal run expands and contracts. Lateral braces are used to control side-to-side movement.

Horizontal three point suspension spring hangers absorb the movement induced by expansion and contraction of the vertical run. Seasonal and daily temperature changes will cause several inches of movement relative to the tower due to the difference in thermal coefficient of expansion of the steel tower and copper transmission line. The temperature of the transmission line under operation will be different than the ambient and tower temperature.

All vertical spring hangers should have the spring tension set to accommodate the local mean temperature. The hanger spring tension charts, supplied for temperature changes, are to be used as a guide. Free movement is essential and should be verified by tracking expansion and contraction through a daily cycle.

Transmission Line Materials

All MYAT copper coaxial transmission lines are fabricated using the purest hard drawn seamless copper tubing for low attenuation. Outer Conductors: Alloy CDA110. Inner conductors: Alloy CDA102.

Inner conductors for connectors, transformers, elbows, power combiners and dividers, etc., are silver plated to military specifications to insure superior performance.

Inner conductor supporting structures are manufactured only from pure virgin PTFE (Teflon) to insure proper performance under peak power conditions.

Peak Power Rating and Production Test Voltages

The following table lists current peak power ratings for all MYAT transmission lines with the following standard conditions: VSWR = 1:1, zero modulation and one atmosphere absolute dry air pressure at sea level (0 lb. PSIG or 14.7 PSIA).

LINE SIZE	Zo	Production test voltage @ 20°C	RF Voltage Limit	Peak Power (watts)
7/8"	50	5825	1442	41600
1 5/8"	50	10409	2576	132700
3 1/8"	50	18971	4695	440900
4 1/16"	50	24076	5959	710100
6 1/8"	50	35411	8764	1536100
6 1/8"	75	36179	8954	1069000
7 3/16"	75	41788	10342	1426100
8 3/16"	75	47273	11699	1825000
8 3/16"	50	46460	11498	2644200
9 3/16"	50	51879	12839	3296900
9 3/16"	75	52730	13050	2270700
12"	50	68336	16912	5720500

Production Test Voltage Equation

$$E_p = 3.17(10)^4 a \delta \left(\log_{10} \frac{b}{a} \right) \left(1 + \frac{0.273}{\sqrt{a \delta}} \right)$$

E_p = Production Test Voltage DC or Peak AC

a = Inner conductor O.D. in inches

b = Outer conductor I.D. in inches

δ = Air density factor = 3.92B/T

where B = Absolute pressure in cm of mercury

T = Temperature in °K

δ = 1.0168 for B = 76 cm,
(29.92") and T = 293°K, (20°C)(68°F)

Radio Frequency Operating Voltage Equation

$$E_{rf} = \frac{0.7 E_p}{SF \sqrt{2}}$$

E_{rf} = RF Operating Voltage, maximum operating voltage

E_p = Production Test Voltage DC or Peak AC

SF = Safety factor, industry standard = 2

Peak Power Rating Equation

$$P_{PK} = \frac{E_{rf}^2}{Z_0}$$

P_{PK} = Peak Power Rating in Watts

E_{rf} = RF operating voltage, maximum operating voltage

Z_0 = Characteristic Impedance

Wavelength Equation

Wavelength in feet.

$$\lambda = \frac{984}{F_{MHz}}$$

Wavelength in meters.

$$\lambda = \frac{300}{F_{MHz}}$$

Skin Depth Equation

$$\delta = \frac{1}{2\pi} \sqrt{\frac{\lambda P}{30\mu}}$$

δ = Skin Depth at rating temperature (cm)

λ = Free Space Wavelength (cm) at frequency of interest

P = Material Resistivity (Ohm-cm) at rating temperature

μ = Permeability of Conductor (Unity for non-magnetic)

Attenuation Due To Conductor Losses Equation

$$\alpha_c = \frac{13.6}{\lambda} \left(\frac{\delta_a \mu_a}{a} + \frac{\delta_b \mu_b}{b} \right) \frac{\sqrt{\epsilon}}{\ln \frac{b}{a}} \text{ db/unitlength}$$

α_c = Attenuation due to conductor losses, db/unit length

δ_a = Skin depth at frequency and rating temperature of inner conductor

μ_a = Permeability of inner conductor,
(unity for copper and aluminum, non-magnetic)

δ_b = Skin depth at frequency and rating temperature of outer conductor

μ_b = Permeability of outer conductor,
(unity for copper and aluminum, non-magnetic)

λ = Free Space Wavelength

a = Radius of outside of inner conductor

b = Radius of inside of outer conductor

ϵ = Dielectric Constant of air (1.0006)

Average Power Rating

$$P_{ave} = \frac{16380 D \sigma}{\alpha_{appl}}$$

P_{ave} = Calculated average power

σ = Heat Transfer coefficient of specific line size and design

D = Outside diameter of outer conductor

α_{appl} = Attenuation in dB/100' for application.

1) At rating temperature

2) Corrected value for application temperature

3) Measured value under power at equalized temperature

Heat Transfer Coefficient Of Specific Line Size and Design						
Line Size	Zo	MYAT Catalog Series	Outer I.D.	σ	Inner Material	Outer Material
7/8"	50	101	0.785	0.1280	Copper	Copper
1 5/8"	50	201	1.527	0.1200	Copper	Copper
3 1/8"	50	301	3.027	0.1070	Copper	Copper
4 1/16"	50	401	3.935	0.1035	Copper	Copper
6 1/8"	50	601	5.981	0.0970	Copper	Copper
6 1/8"	75	701	5.981	0.0770	Copper	Copper
7 3/16"	75	775	7.000	0.0760	Copper	Copper
8 3/16"	75	801	8.000	0.0740	Copper	Copper
8 3/16"	50	851	8.000	0.0920	Copper	Copper
9 3/16"	50	901	9.000	0.0900	Copper	Copper
9 3/16"	75	971	9.000	0.0692	Copper	Copper
12"	50	1201	12.000	0.0860	Copper	Aluminum

Efficiency

$$Efficiency = \frac{100}{10^{\left(\frac{dB}{10}\right)}} \%$$

dB= Total System Attenuation, calculated or measured

Characteristic Impedance

$$Z_o = \frac{138}{\sqrt{\epsilon_{eff}}} \log_{10} \frac{D}{d}$$

D = Inside diameter of outer conductor
 d = Outside diameter of inner conductor
 ϵ_{eff} = Effective dielectric constant

Impedance Matching Quarter-Wave Transformer

$$Z_T = \sqrt{Z_I Z_O}$$

Z_T = Transformer Impedance
 Z_I = Input Impedance
 Z_O = Output Impedance

Impedance Matching Two Quarter-Wave Transformers

$$Z_1 = \sqrt[4]{Z_I^3 Z_O}$$

Z_1 = Transformer 1 Impedance
 Z_I = Input Impedance
 Z_O = Output Impedance

$$Z_2 = \sqrt[4]{Z_I Z_O^3}$$

Z_2 = Transformer 2 Impedance
 Z_I = Input Impedance
 Z_O = Output impedance