Technical Description RF Cables

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Mechanical characteristics

Tensile strength

The tensile strength of RF cables is determined by the configuration and cross section of the conductors. In the case of corrugated conductors, tensile strength is naturally less than in the case of smooth conductors. To prevent damage to the cable, when hoisting it into masts or pulling it through ducts, the maximum admissible tensile force stated for the particular cable must not be exceeded. The values stated are based on the assumption that both conductors are firmly attached to each other so that they will both carry weight (respectively force). Refer to the installation instructions for further details.

Bending properties

A particular advantage of RF cables with corrugated conductors is their flexibility, as expressed in the data for minimum admissible bending radii.

For single bending

After the cable has been bent to these minimum values it should not be bent back, as this could result in damage to the cable.

Repeated bending
This bending radius allows for several operations and indicates the minimum admissible bending radius during the installation procedure of the cable. It also gives an indication of the minimum admissible reel core radius.

Crush resistance

Another advantage of the outer conductor corrugation is the fact that it gives the cable a very high crush resistance. As an example, the following figures are given: In order to compress a 90 mm length section of FLEXWELL HF 7/8" by 1% of its diameter, it is necessary to apply a force of 4000 N.

Sealing and pressurization

FLEXWELL cables are gas tight and can, therefore, (for monitoring purposes or in order to prevent condensation or ingress of moisture) be filled with dry air or nitrogen of 0.1 to 0.3 bar overpressure.

In addition, the power rating of FLEXWELL cables may be greatly increased by operating them under an inner overpressure of for example 3 bar, with dry air, nitrogen or with gases. End termination (connectors) and cable couplings suitable for this type of high pressure operation are available for FLEXWELL cable sizes 3" to 9". During manufacture, cables for high pressure operation are subjected to a special sealing test.

Transmission line parameters

Primary and secondary transmission line parameters

The relation between the primary parameters

series resistance	R' in Ω/km
inductance	L' in H/km
parallel capacitance	C' in F/km
parallel resistance	G' in S/km

and the secondary parameters

characteristic impedance	Z_c in Ω
propagation constant	γ
phase constant	β in rad/km
attenuation constant	α in N/km

is given by the following transmission line equations:

$$g = a + jb$$

$$g = \sqrt{(R' + jwL') \cdot (G' + jwC')} \qquad (1)$$

$$Z_c = \sqrt{(R' + jwL') / (G' + jwC')} \qquad (2)$$

$$w = 2pf$$

These equations are valid for the entire frequency range of RF cables up to their cut-off frequency.

At radio frequencies where R' « ωL' and G'« ωC', the transmission line equations take the following form:

$$Z_c = \sqrt{\frac{L'}{C'}} \qquad \text{in } \Omega \qquad (3)$$

$$b = w \cdot \sqrt{L' \cdot C'} \qquad \text{in rad/km} \qquad (4)$$

$$a = (R'/2) / Z_c + (G'/2) \cdot Z_c \qquad \text{in N/km} \qquad (5)$$

$$= a_R + a_G$$

$$v_j = 1 / \sqrt{L' \cdot C'} \qquad \text{in km/s} \qquad (6)$$

a_R - conductor attenuation
a_G - dielectric attenuation
v_j - propagation velocity

The deviations between equations (3) to (6) as compared to equations (1) and (2) is below 0.1%, as long as

$$D_e \sqrt{f} \geq 140 \qquad (7)$$

D_e - electrically equivalent diameter of outer conductor in mm
f - frequency in kHz

Skin effect

At DC, current in a conductor flows with uniform density over the cross section of the conductor. At high frequencies, the current tends to flow only in the conductor surface; the effective conductor cross section decreases and the conductor resistance increases.

At radio frequencies, current flows only in a very thin "skin". Everywhere else the conductors are free from electromagnetic fields. Even very thin walled metal envelopes will, therefore, entirely screen the electromagnetic field within coaxial RF cables at radio frequencies.

The depth of penetration illustrates the skin effect. It is defined as the thickness of a thin surface layer (assumed to have an even distribution of current flow), having the same resistance as an actual conductor which is undergoing to the skin effect.

For non-magnetic materials the equivalent conducting layer is

$$d = 15{,}9 / \sqrt{s \cdot f}$$ in mm (8)

s - conductivity in m/Ω mm^2

f - frequency in kHz

Other than resistance, the skin effect also influences inductance and thereby characteristic impedance and propagation velocity.

Electrical characteristics

Capacitance

The capacitance of RF cables is independent of frequency:

$$C' = \frac{10^{-6} \cdot e_r}{18 \cdot \ln(D_c / d_c)}$$ in F/km (9)

e_r - relative dielectric constant

D_c - effective outer conductor diameter (capacitive)

d_c - effective inner conductor diameter (capacitive)

Inductance

The inductance of a RF cable is:

$$L' = 2 \cdot 10^{-4} \cdot ln \frac{D_i + d}{d_i - d}$$ in H/km (10)

D_i - effective inner conductor diameter (inductive)

d_i - effective inner conductor diameter (inductive)

d - equivalent conducting layer

At very high frequencies, inductance approaches:

$$L' = 2 \cdot 10^{-4} \cdot ln(D_i / d_i)$$ in H/km (11)

Characteristic impedance

The characteristic impedance of an RF cable is determined by its inductance and capacity according to equation 3. Because of the influence of the skin effect upon inductance, it also is frequency-dependent.

Characteristic impedance of RF cables is, therefore, understood as the value it approaches for very high frequencies. If we say $D_c \approx D_i = D_e$, $d_c \approx d_i = d_e$ and $\delta \ll d_i$, then

$$Z_c = \frac{60}{\sqrt{e_r}} \cdot ln(D_e / d_e) \qquad \text{in } \Omega \qquad (12)$$

D_e - electrically effective outer conductor diameter
d_e - electrically effective inner conductor diameter
e_r - relative dielectric constant

As frequency falls, the characteristic impedance rises. The relative deviation from the value at very high frequency is approx.

$$\frac{\Delta Z}{Z_c} = \frac{4}{D_e \cdot \sqrt{f}} \qquad (13)$$

D_e - electrically effective outer conductor in mm
f - frequency in kHz

Certain electrical properties of an RF cable can be optimized by proper choice of characteristic impedance. For coaxial cables with cylindrical conductors (of the same material) the following optimizations are possible:

	air dielectric cables	solid PE dielectric cables
minimum attenuation	77 ohms	51 ohms
max. operating voltage	60 ohms	40 ohms
max. peak power rating	30 ohms	20 ohms
max. mean power rating	≈ 50 ohms*	

*approx. valid for FLEXWELL transmission lines of larger diameter

Today, RF coaxial cables are produced mainly with characteristic impedance of 50 ohms and to some extend in 75 ohms.

As the material properties and dimensions of RF cables are not constant along their length, the characteristic impedance will vary with length and deviate from the mean value of characteristic impedance of the particular cable; similarly the mean value will deviate from the nominal value (50 or 75 ohms).

The mean value of characteristic impedance of a cable is defined as follows:

$$Z_m = \frac{l_e}{c_o \cdot C} \qquad \text{in ohms} \qquad (14)$$

l_e - electrical length in m

c_o - propagation velocity in free space in m/sec

C - capacitance in F

The mean value of characteristic impedance is measured at around 200 MHz. The admissible deviation from the nominal value is ± 1% to ± 4%, depending on the product group.

Uniformity of characteristic impedance

As mentioned, the material properties of RF cables are not uniform along their length and result in small deviations of the characteristic impedance. The impedance step ΔZ at position x of the cable results in reflection factor at the position as follows:

$$r_x = \frac{\Delta Z}{2Z_c} \qquad (15)$$

The magnitude and distribution of the various reflections determine their effect upon transmission properties. Two ways are commonly used to judge the effect of impedance variation.

Time domain reflectometry (TDR)

A defined voltage step is fed into the cable and partially reflected at each impedance variation. The display of the reflected energy versus time gives a view upon the local distribution of the inner reflections. The pulse reflection factor at a certain position is the ratio between the voltage of the reflected and the incident pulse. Instead of reflection factor, one can also use the term pulse return loss:

$$A_p = 20 \cdot \log \frac{100}{r_p} \qquad \text{in dB} \qquad (16)$$

r_p - pulse reflection factor in %

The magnitude and nature of the pulse reflection factor depend very much upon the form of incident pulse.

Return loss/reflection factor (steady state condition)

The reflection factor sums up the effects of all the impedance variations within the cable and its ends, at a certain frequency. It is the ratio between the (vectorial) addition of all reflections and the incident signal, measured at the near end of the cable.

As well as reflection factor, the term return loss is also used.

$$A_Z = 20 \cdot \log \frac{100}{r} \qquad \text{in dB} \qquad (17)$$

r - reflection factor in %

The reflection factor may be plotted continuously versus frequency. The reference impedance of test equipment and the load at cable end are equal to the nominal value of cable impedance.

It is also customary to use the term voltage standing wave ratio (VSWR), based upon the standing wave, which the cable under test would produce in a homogeneous transmission line connected to its near end and having its nominal characteristic impedance.

$$s = \frac{1 + r/100}{1 - r/100} \qquad (18)$$

$$r = \frac{s-1}{s+1} \cdot 100 \text{ in \%} \qquad (19)$$

s - standing wave ratio

Relative propagation velocity and delay

The relative propagation velocity is defined as follows.

$$v_r = \frac{u_j}{c_o} \cdot 100 = \frac{l}{l_e} \cdot 100 \qquad \text{in \%} \qquad (20)$$

u_j - propagation velocity in cable

c_o - propagation velocity in free space $(300 \cdot 10^3 km/s)$

l - geometrical length in m

l_e - electrical length in m

Delay is defined as follows:

$$t_j = \frac{333{,}6}{v_r} = \frac{10^8}{v_r \cdot c_o} \qquad \text{in ns/m} \qquad (21)$$

v_r - relative propagation velocity in %

Due to the skin effect, propagation velocity is frequency dependent. Velocity decreases with falling frequency, delay increases. The relative deviation can be calculated according to equation 13.

As in the case of characteristic impedance, relative propagation velocity of RF cables is understood as the value it approaches for very high frequencies. If $D_c = D_i$ and $d_c = d_i$ it is dependent solely upon the dielectric constant ε_r and is as follows:

$$v_r = \frac{100}{\sqrt{e_r}} \qquad \text{in \%} \qquad (22)$$

Propagation velocity is measured at frequencies around 200 MHz as standard. Propagation velocity is also subject to variations. These variations have no direct influence upon transmission characteristics; they do, however, come to light, if cables have to be adjusted to equal electrical length, because after adjustment the cables of equal electrical length may show differences in geometrical length. If cables are to be used in applications where consistency of electrical length is important, we recommend that this is stated at the time of order placement, in order to allow us to select the cables from one manufacturing batch, whenever possible.

Electrical length and adjustment of length

The electrical length is defined as follows:

$$l_e = \frac{100 \cdot l}{v_r} \qquad \text{in m} \qquad (23)$$

l - geometrical length in m
v_r - relative propagation velocity in %

Between electrical length and phase angle the following relation applies:

$$j = 2 \cdot p \cdot \frac{l_e}{300} \cdot f \qquad \text{in rad} \qquad (24)$$

l_e - electrical length in m
f - frequency in MHz

In many cases, cables with equal or defined differential electrical length are required. Typical examples are feeder cables for TV transmitters and cabling of antenna groups or antenna arrays. Such length adjustments can be made with precision. A typical value for the achievable accuracy is a phase angle tolerance of ± 5° in the 470 to 860 MHz frequency band. In order to eliminate length variations through handling after adjustment, we recommend to have long lengths of cables length adjusted after installation; short cable lengths may, however, be supplied factory-adjusted.

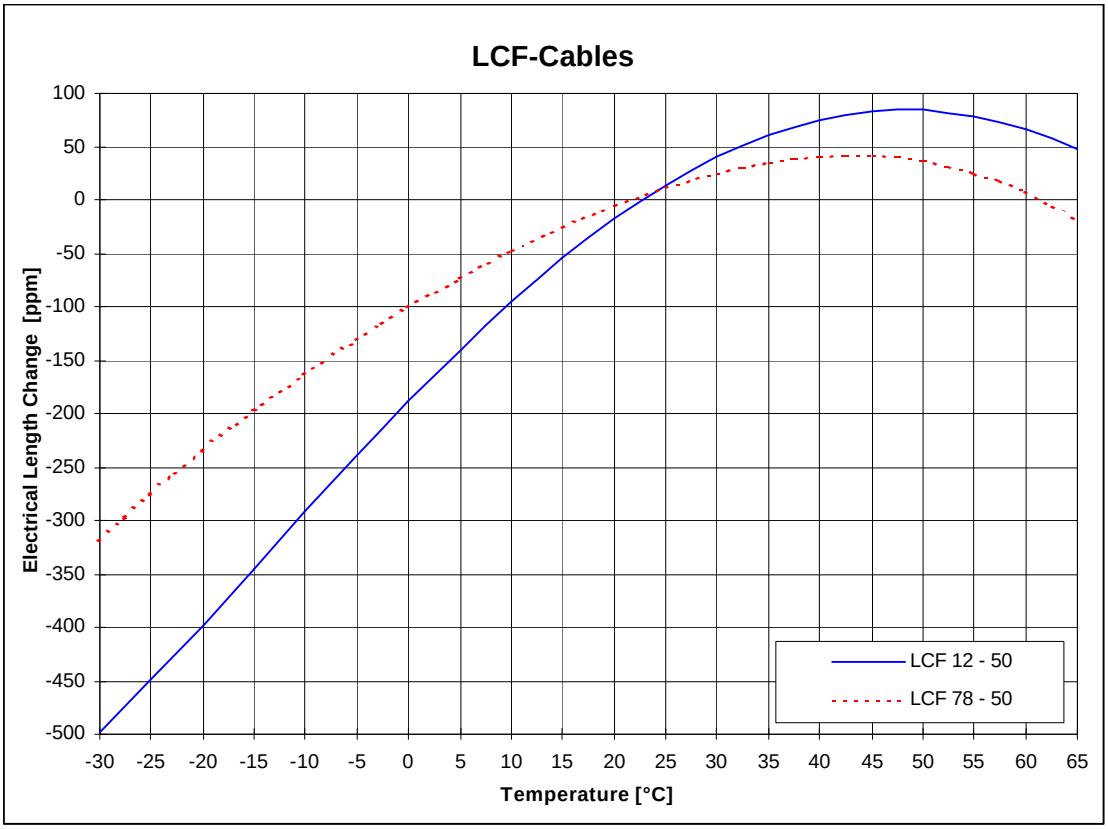
The electrical length of RF cables is dependent upon temperature, and in case of air dielectric cables also upon the pressure and humidity of contained air. The influences are quite small, but must, however, be taken into account in case where the cables are very long as compared to the operating wavelength.

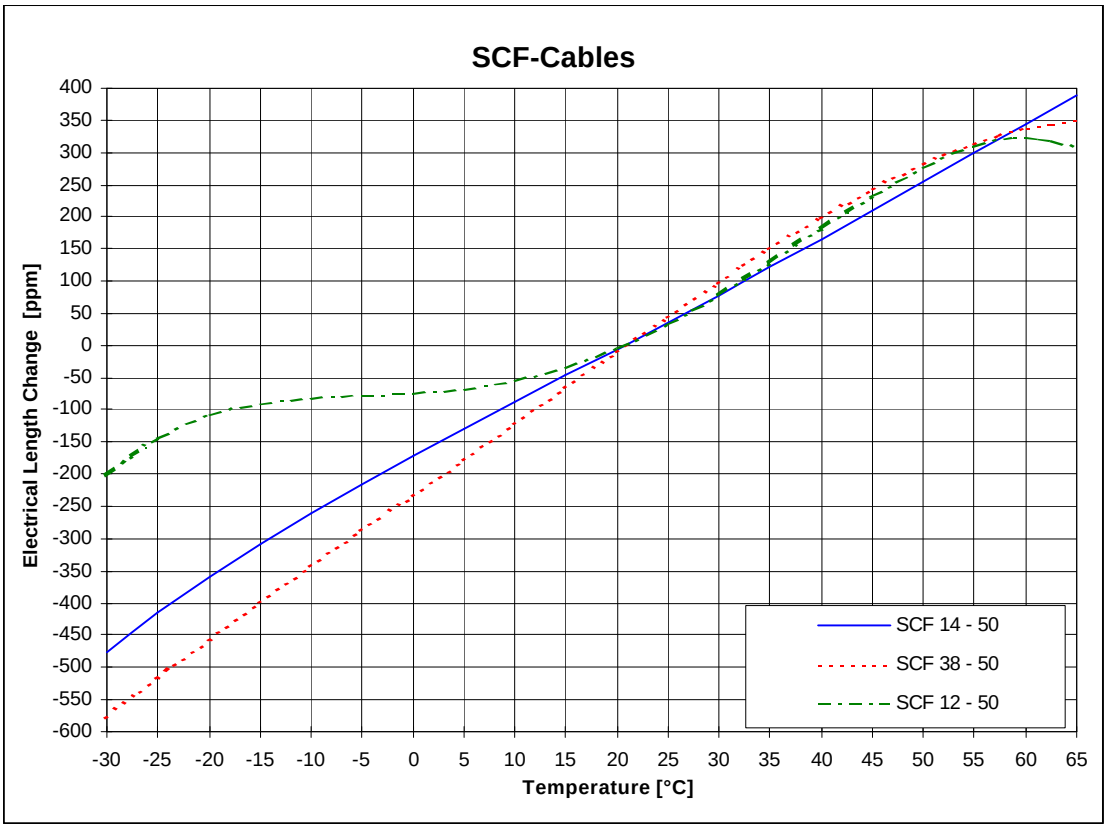
It is advisable to install length-adjusted cables so that they are all subject to the same ambient conditions such as temperature, solar radiation etc. Length-adjusted FLEXWELL cables should be operated under a slight overpressure (the same for all cables) of approx. 0.2 bar of dry air or nitrogen.

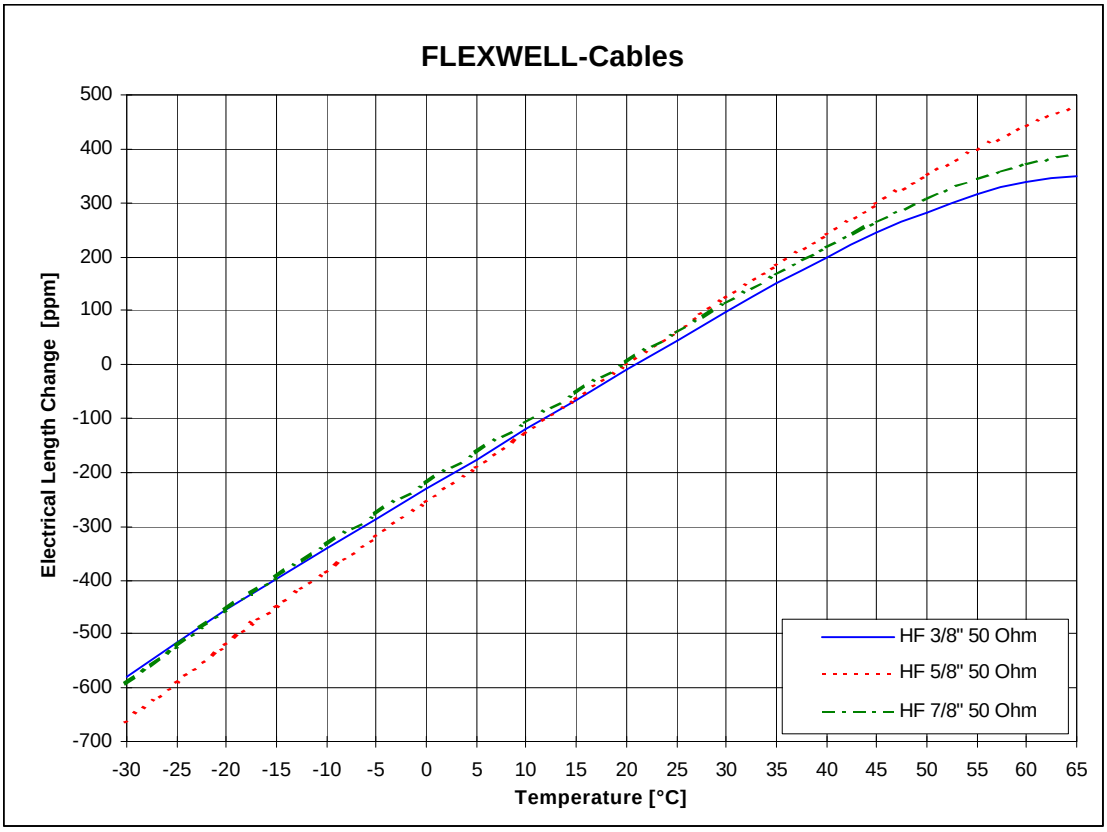
For less critical applications, phase-stabilized cables can be supplied. These are cables that are aged in order to reduce hysteresis effects.

The variation of electrical length with temperature is also influenced by the kind of cable attachment to the support structure. Cables that can expand freely with temperature have different values than cables which are rigidly clamped down.

In the following diagrams typical figures of the electrical length change are shown for several cable types.







The phase change for a given cable length and temperature range can be calculated with equation (25).

$$\Delta j = 120 \cdot 10^{-6} \cdot \frac{l}{v_r} \cdot \Delta ppm \cdot f \qquad \text{in Deg} \qquad (25)$$

l	-	cable length	in m
v_r	-	realtive velocity of propagation	in %
Δppm	-	electrical length change	in ppm
f	-	frequency	in MHz

Example:
A 10 m run of LCF 12-50 is used in the temperature range from -10°C to 40°C at 1 GHz.

In the above diagram the $Dppm$ of approximately 370 can be read. The maximum phase change is $\Delta j = 120 \cdot 10^{-6} \cdot \frac{10}{88} \cdot 370 \cdot 1000 = 5.0°$.

Attenuation

The attenuation of RF cables is defined as follows:

$$a = 10 \cdot \log(P_1 / P_2) \qquad \text{in dB/100 m} \qquad (26)$$

P_1 - input power into a 100 m long cable terminated with the nominal value of its characteristic impedance

P_2 - power at the far end of this cable

The construction of a cable influences the attenuation (in the case of copper conductors and at 20°C) in accordance with the following equation:

$$a_{20} = \frac{36{,}1}{Z_C}\left(\frac{k_i}{d_e} + \frac{k_a}{D_e}\right) \cdot \sqrt{f} + 9{,}1\sqrt{e_r} \cdot tg\, d \cdot f$$
$$= a_R + a_G \qquad \text{in dB/100 m} \qquad (27)$$

Z_c	- characteristic impedance in ohms
f	- frequency in MHz
D_e	- electrically equivalent outer conductor diameter in mm
d_e	- electrically equivalent inner conductor diameter in mm
ε_r	- relative permittivity of dielectric
tgδ	- loss factor of dielectric
k_i	- shape factor of inner conductor
k_a	- shape factor of outer conductor

The attenuation values are stated for 20 °C. The stated figures are typical. With rising ambient temperature the attenuation also rises, by 0,2%K. The attenuation also rises if the cable is heated up by the transmitted power. The maximum rise is as follows:

FLEXWELL cable with PE dielectric $a_t / a_{20} = 1.14$
FLEXWELL cable with teflon dielectric $a_t / a_{20} = 1.20$
CELLFLEX cable $a_t / a_{20} = 1.12$

a_t - attenuation of the cable at full mean power rating

Finally, attenuation rises in case of considerable mismatches at the cable end. The effect is illustrated in Fig. 1. The cable is assumed to be matched at the transmitter.

The attenuation of RF cables is mainly resistive attenuation α_R, which rise with the square root of frequency. For a given cable size, the resistive attenuation reaches a minimum for a dielectric constant of 1 (air dielectric). Resistive attenuation also decreases with increasing cable size.

Dielectric attenuation α_G rises proportionally with frequency. It is independent of cable size and determined only by quantity and quality of the dielectric material. Its share in total attenuation rises with frequency and cable size. Therefore, in particular the larger FLEXWELL cable sizes have a very low material content dielectric. The same fact also prompted the introduction of loss foam CELLFLEX cables (LCF).

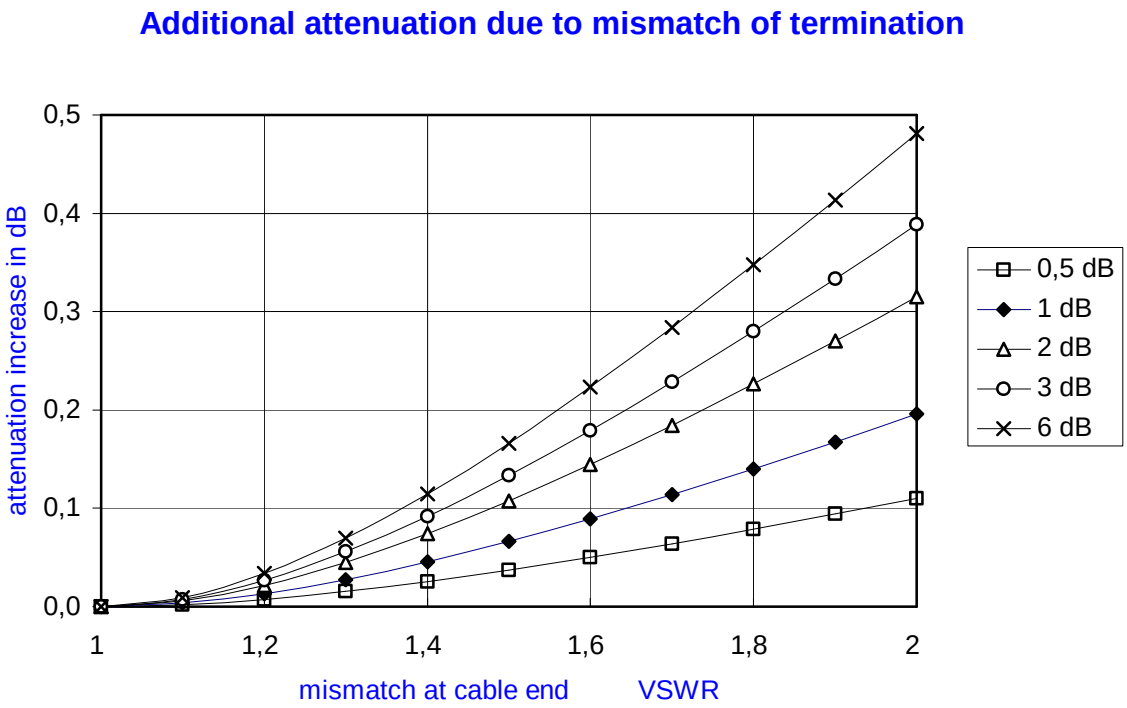


Fig. 1 Attenuation increase due to mismatch at cable end (with cable matched at transmitter end)

Efficiency

The efficiency of a cable is the ratio between the power available to a load at the far end of the cable and the power put into it at the near end and is therefore an important parameter to compare several feeder cables.

$$h = \frac{P_2}{P_1} = 10^{-\left(\frac{a_t \cdot \frac{l}{100} + A_r}{10}\right)} \qquad (28)$$

P_2 - power at load
P_1 - input power
α_t - attenuation of cable (taking into account additional attenuation due to the power being used) in dB/100 m
A_r - additional attenuation through mismatch at cable end (see Fig.1)
l - cable length in m

Power rating

Power rating is the lower of the following two values: peak power rating and mean power rating.

Peak power rating

Peak power rating is the input power for which the peak RF voltage rating is reached, when the cable is operating in its matched condition. It is defined as:

$$\hat{P} = 500 \cdot \frac{\hat{U}^2}{Z_C} \qquad \text{in kW} \qquad (29)$$

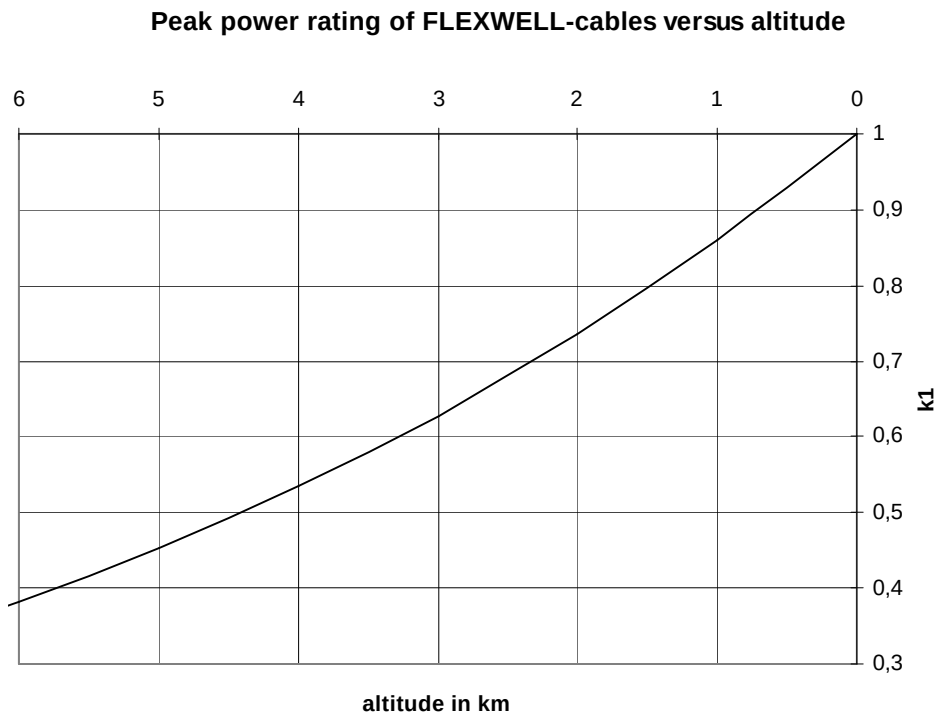
$\hat{U}$ - -RF voltage rating (peak value) in kV
Z_C - characteristic impedance in Ω

Peak power rating is independent of frequency. The stated values for peak RF voltage rating and peak power rating of FLEXWELL cables are valid for dry air or dry nitrogen under normal atmospheric pressure.

As production testing of RF cables is done with DC voltage of twice the peak RF voltage rating, there is a safety factor of 2 in voltage and a safety factor of 4 in peak power rating.

Peak power rating of FLEXWELL cables can be increased considerably by operating them under inner overpressure (suitable connectors for this operation are available for cable, sizes 3" and larger). Peak power rating decreases with altitude, if the cable inner is allowed to assume the pressure of the environment, see. Fig. 2.

Although CELLFLEX cables due to their dielectric type have a higher voltage strength than air dielectric cables, in practice the short sections of air line present at the cable ends when terminated with commonly used connector types limit the peak voltage ratings of CELLFLEX cables to those of equivalent size air dielectric cables.



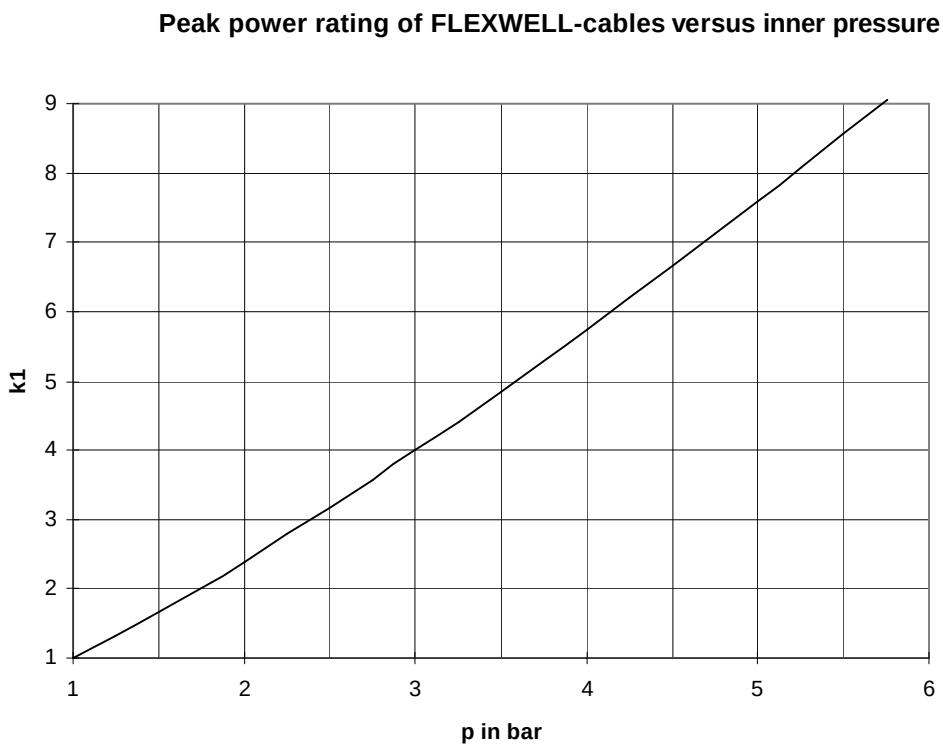


Fig. 2 Peak power rating of FLEXWELL cables versus inner pressure and altitude

Mean power rating

Mean power rating is defined as:

$$\overline{P}_{max} = \frac{0{,}8686 \cdot P_v}{2 \cdot a_t} \qquad \text{in kW} \qquad (30)$$

P_v - maximum admissible power dissipation in W/m

a_t - attenuation under operation condition in dB/100 m

Mean power rating is the input power at which the inner conductor reaches a temperature agreed for a certain dielectric material. For most of the RFS cables these are:

FLEXWELL (teflon)	150°C
FLEXWELL (polyethylene)	115°C
CELLFLEX	100°C

Mean power rating decreases as frequency rises.

Mean power rating values are given for the following conditions:

installed in still air of 40 °C
in case of FLEXWELL cables, filled with air or nitrogen, under normal atmospheric pressure.

The variation of mean power rating with ambient temperature is given in Fig. 3.

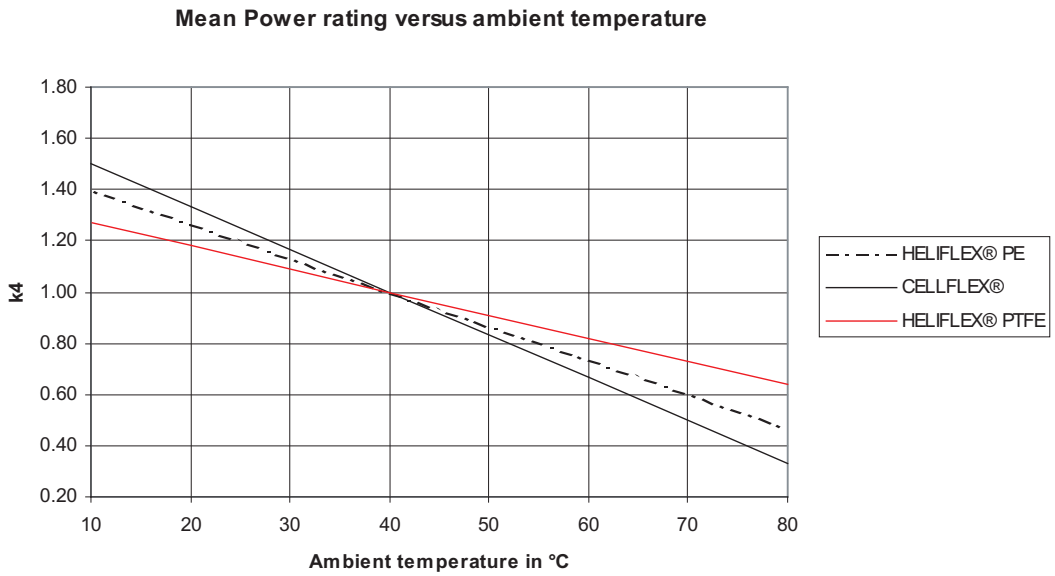


Fig. 3 mean power rating versus ambient temperature

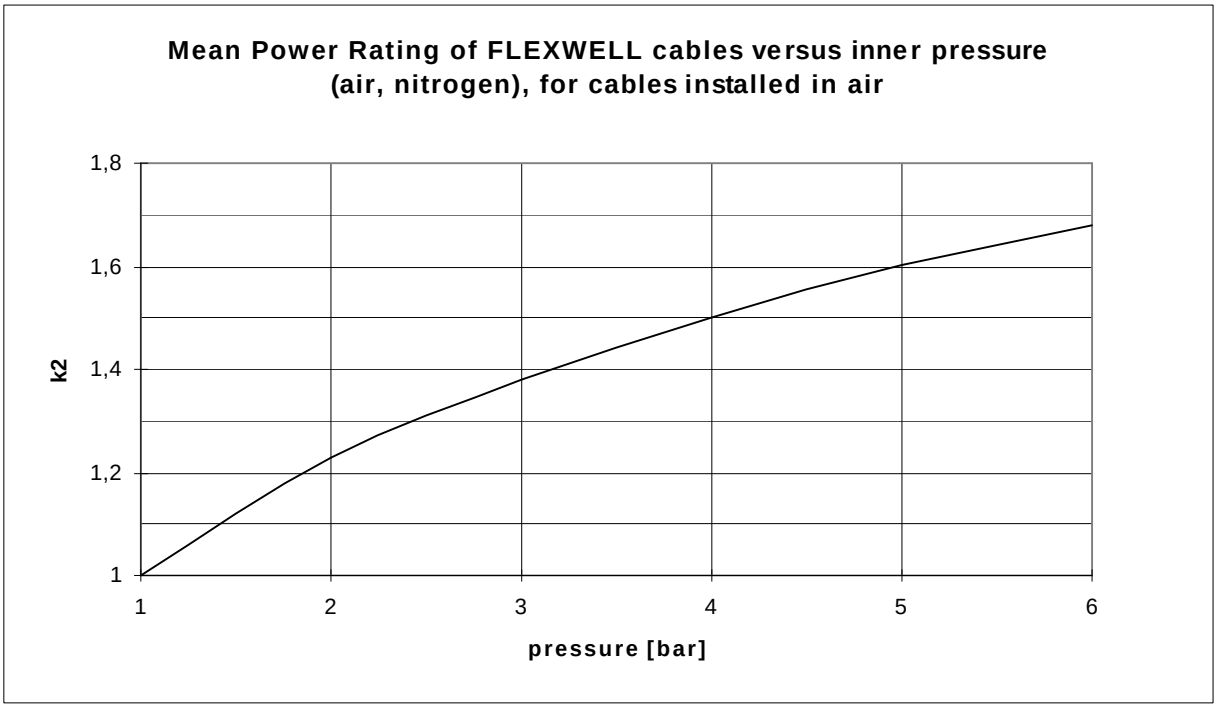


Fig. 4 Mean power rating of FLEXWELL cables versus inner pressure (air, nitrogen) for cables installed in air

If RF cables are subjected to direct solar radiation, mean power rating will decrease. The derating factor is given in Fig. 5.

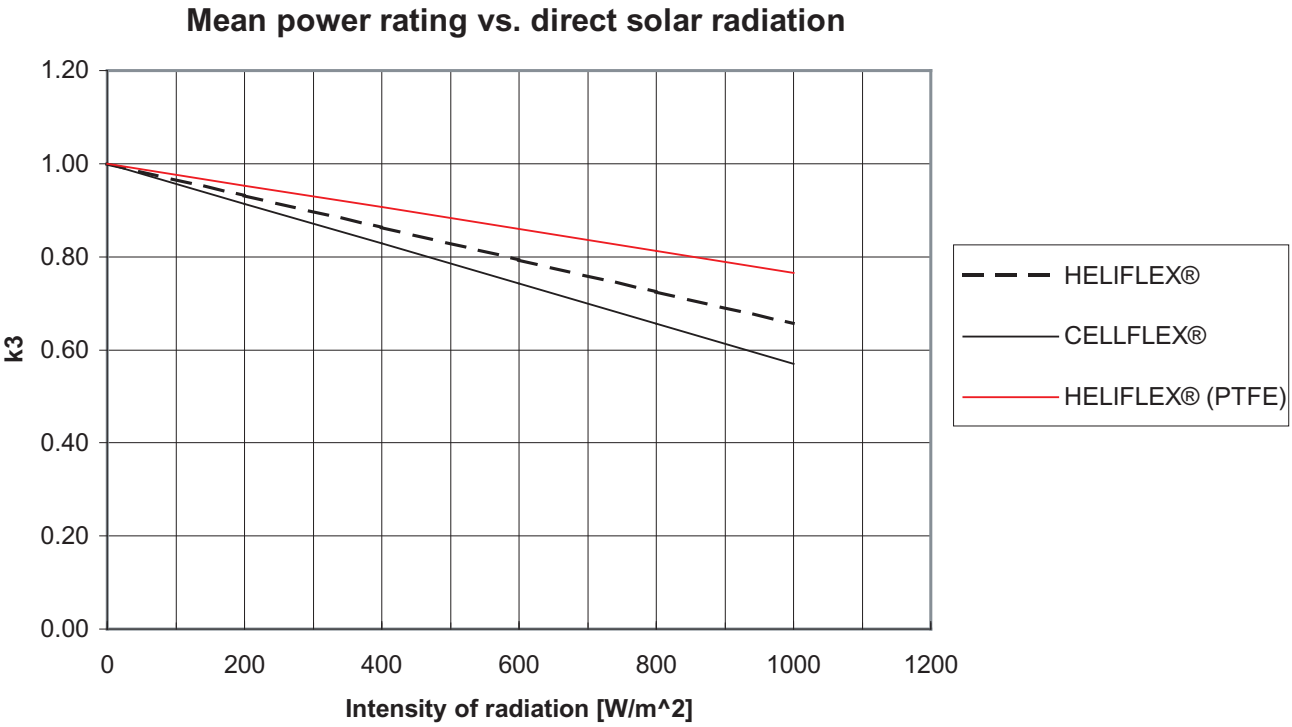


Fig. 5 Influence of direct solar radiation upon mean power rating. Worst case: cable fully exposed and at right angles to sun rays

For mean power calculation of cables to be buried in the ground, the heat resistance of the cable jacket to air combination is replaced by the heat resistance of the soil, and the ambient temperature is replaced by the average soil temperature at the proposed cable laying depth.

As the heat resistivity of the soil is very dependent upon local conditions such as humidity, type of soil, and since the soil in the vicinity of RF cables which dissipate large heat power tends to dry out, it is necessary to have the correspondent information from the list given below.

Generally, it can be said for normal kinds of soil in moderate climates, that mean power rating of smaller cable sizes if buried increases whereas in the case of larger cable sizes it decreases.

If a buried, large cable is operating under inner overpressure, mean power rating doesn't increase as much as if this cable would be installed above ground.

When planning an RF cable system the following Data should be known:

Installation location details:

height above sea level
ambient temperature and intensity of solar radiation
ground temperature, soil type and ground water level

Installation details:

cable to be laid in masts, above, in the ground or in ducts
pressurization permissible
local heating due to parallel cables
connector types

Operating conditions:

number and length of cables
frequencies and permissible attenuation
transmitter peak and average output power ($\hat{P}$ and $\overline{P}$)
or the information to calculate these data, as given in Fig.6
antenna VSWR (s)

If the cable end is not terminated in its characteristic impedance, standing waves along the cable will result in higher power being dissipated at current and voltage maxima. Input power must, therefore, be reduced accordingly. In summary, therefore, the following conditions must be fulfilled when selecting a cable size for a certain power configuration.

$$\hat{P}_{max} \geq \frac{\hat{P} \cdot s}{k_1} \qquad (31)$$

$$\overline{P}_{max} \geq \overline{P} \frac{s}{k_2 k_3 k_4} \qquad (32)$$

$\hat{P}, \overline{P}$	- peak power and mean power of transmitter
$\hat{P}_{max}, \overline{P}_{max}$	- peak power rating and mean power rating of cable
s	- VSWR
k_1	- peak power rating factor for inner pressure (Fig.2)
k_2	- mean power rating factor for inner pressure (Fig.4)
k_3	- mean power rating factor for direct solar radiation (Fig.5)
k_4	- mean power rating factor for ambient temperature (Fig.3)

For cables operated above half their cut-off frequency in a non-matched condition, heat compensation between the extreme values of temperature along the cable can be expected. In this case, the VSWR in equation 32 may be replaced by the term $(s^2 + 1)/2\ s$.

If peak and average transmitter output power are known only in terms like carrier power, modulation depth etc., then these data can be computed as follows:

$$\hat{P} = P_R \cdot \hat{q} \qquad (33)$$

$$\overline{P} = P_R \cdot \overline{q} \qquad (34)$$

P_R	- reference power of transmitter
$\hat{q}$	- factor according to Fig.6
$\overline{q}$	- factor according to Fig. 6

Modulation	Reference Power P_R	$\hat{q}$	$\overline{q}$
amplitude modulation	carrier power	$(1+\hat{m})^2$	$1+\frac{\overline{m}^2}{2}$
frequency modulation	transmitter power	1	1
pulse modulation	pulse power	1	$t_p \cdot f_p$
television (CCIR Standard)	peak sync. Power	1.73 [1)] 1.50 [2)]	0.71 [1)] 0.66 [2)]
DAB OFDM	sum power	10 [3)]	1
DVB OFDM	sum power	10 [3)]	1

Fig. 6

[1)] audio to video power ratio 1:10

[2)] audio to video power ratio 1:20

[3)] Depending on the number of carriers, the theoretical value of $\hat{q}$ can be very high. In practice, $\hat{q}$ is limited to about 10 by saturation effects of the transmitter output amplifier.

$\hat{m}$ - peak modulation depth
$\overline{m}$ - mean modulation depth
t_p - pulse length in ms
f_p - pulse repetition frequency in MHz

If several programs with peak power values P_1,P_2, etc., are transmitted simultaneously, then the resulting peak power is as follows:

$$\hat{P}_{res} = (\sqrt{\hat{P}_1} + \sqrt{\hat{P}_2} + \ldots\ldots\ldots)^2 \qquad (35)$$

Maximum operating frequency and cut-off frequency

Energy transmission in a coaxial RF cable takes place in the normal coaxial wave mode. Above cut-off frequency, which is a function of cables dimensions, other wave modes can also exist and the transmission properties are no longer defined. It is, therefore, generally not possible to operate RF cables above their cut-off frequency. An approximate value of cut-off frequency and the cut-off wavelength for RF cables can be computes as follows:

$$f_c = \frac{1{,}91 \cdot v_r}{D_i + d_a} \qquad \text{in GHz} \qquad (36)$$

$$l_c = p\,\frac{D_i + d_a}{2} \cdot \frac{1}{10 \cdot v_r} \qquad \text{in m} \qquad (37)$$

v_r - relative propagation velocity in %
D_i - inner diameter of outer conductor in mm
d_a - outer diameter of inner conductor in mm

In addition to cut-off frequencies, maximum operating frequencies of RF cables are stated. These give a certain safety margin from cut-off frequency. For some cables the maximum operating frequency is determined by other construction criteria and may then significantly deviate from cut-off frequency.

Measurements

If no alternative arrangements have been made, then measurements of the electrical properties of RF cables are made in accordance with IEC 61196-1: Radio-Frequency-Cables; Generic specification - General definitions, requirements and test methods.