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INTRODUCTION

The aim of this paper is to review the basic concepts of heat generation and transfer from the standpoint of the technical man with CATV operational responsibility.

The paper will also present some information, which it is hoped will be found useful in solving specific practical problems imposed by the fact that the CATV system must operate over a wide ambient temperature range.

It might be argued that the thermal design problems belong to the equipment designer and to a certain degree this is true. However, it should be pointed out that the final equipment operating temperatures can be strongly influenced by installation techniques and location. The operating engineer or technician is very often much closer to this problem than the designer.

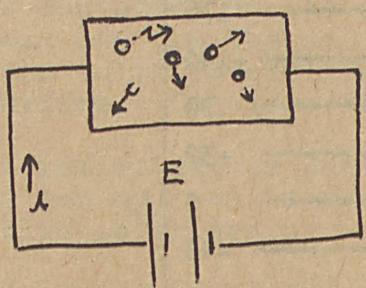
This paper is not suggesting that the operating engineer should plunge into realm of mathematics of heat transfer but rather to point out that the investment of a little time to understanding the principles plus a modest investment in some temperature measuring equipment can pay off in improved reliability and performance.

I have in mind some specific situation where unreliability was "installed in". To illustrate, I know of an installation in a boiler room where a few changes in the housing could have avoided a lot of grief. I suspect also that most pedestal installations are unnecessarily over heated and could be vastly improved by making a few basic changes. I am sure there are many situations where AC input voltage on amplifiers are greater than required, a procedure that usually does nothing more than increase operating temperature.

THE NATURE OF HEAT AND HEAT TRANSFER

Heat is a form of energy, thermal energy. The heat of a body is the total kinetic energy of the random motions of the molecules of the body. In understanding the behavior of heat, it is wise to keep, firmly in mind, this concept of molecules moving at increasing velocity as heat is applied.

Heat is generated by conversion of other forms of energy, such as electrical energy into thermal energy. Hence, if electrical energy is pumped into something like a resistor at a constant rate (constant power input) without providing a means of removing it, the thermal energy of the body (resistor) will increase until something drastic happens to the molecular bonds. As you know, it is the matter of removing the thermal energy from the resistor which presents the practical engineering problems (the study of heat transfer). I have attempted to show schematically the pertinent relations for heat generation and transfer in Figure 1.



Q = TOTAL HEAT

P = ELECTRICAL POWER = HEAT INPUT PER UNIT TIME

Q = CONSTANT + P x ΔT - LOSS TO AIR

Q = $\sum 1/2\, mv^2$ = SUM OF KINETIC ENERGIES

BASIC RELATIONS HEAT GENERATION

FIGURE 1

Fortunately, it is not necessary to have a precise understanding of the physics involved in order to deal with heat. Like many other engineering problems, we handle this by devising ways to measure the thermal state of the bodies and mathematical laws which will predict the behavior of heat and various substances at varying thermal states.

It turns out that one can also draw thermal circuit diagrams in a similar fashion to electrical circuitry. This allows us to conveniently analyze the flow process by familiar electrical methods like Ohm's law. An illustration of these approaches will be covered later in this paper, utilizing a typical pedestal mounted amplifier installation as an example. A summary of important data for use in thermal calculations is included at the end of this paper.

BASIC LAWS AND DEFINITIONS

TEMPERATURE

Temperature is the yardstick which is used to measure the thermal state of a body. It is a measure of the thermal state on some arbitrary numerical scale. The three commonly used scales are compared in Figure 2 at approximate temperatures which concern us in CATV work.

RELATIONSHIP OF VARIOUS TEMPERATURE SCALES

ABSOLUTE	CENTIGRADE	FAHRENHEIT
+374	+100	212
353	+80	176
333	+60	+140
294	+21	70
+273	0	+32
+256	-17	0
+233	-40	-40
0	-273	-459

FIGURE 2

It should be noted that on the absolute scale the temperature changes which concern us represent a fairly small percentage of the absolute temperature. This is significant, since it turns out that radiation of heat and intrinsic electrical noise are strongly dependent on absolute temperature.

HEAT FLOW

Heat flows from one body or substance to another by three basic processes: conduction, convection or radiation.

CONDUCTION

Conduction is the transmission of heat within the body by means of molecular collision. It involves intimate contact of the materials conducting heat. The thermal energy is propagated by direct collision of the molecules of the material.

The relations for calculating temperature drop are illustrated in Figure 3.

From this it can be seen that the thermal resistance of the body (R) is proportional to the length and inversely proportional to area and conductivity of the material. It can be seen that on the basis of this equation, one can draw a circuit diagram comparable to an electrical circuit representing heat flow rate (i.e., watts or BTU per hour) as a constant current and at temperature difference as potential drop.

CONVECTION

Convection is a similar process to conduction except that a fluid (like air) is involved which must flow over the surface.

In this process heat is transferred by conduction to the fluid, which then carries it away as it moves. The movement of the air may be due alone to the fact that the air is heated or it may be due to some force acting on it. This process tends to get quite complicated since the efficiency of the heat transfer depends on shape of the body, as well as the surface area of which is contacted by the moving air. For practical purposes one can use the thermal resistance concept to visualize and calculate relative efficiencies of a convective heat transfer surface. Consider Figure 4.

The thermal resistance as defined for this body, as well as any similar set up, can be used to analyze and or evaluate any convective interface under varying heat flow.

Specialists have studied in great detail the optimum convection surface and considerable data is available in literature. The main points to remember are that the resistance will decrease with increased surface area; but that the surface area to be effective must not restrict flow. It has also been clearly shown that a "short height" area will transfer heat substantially better than a tall one. This is because the air in rising absorbs heat near the bottom and hence, has less heat absorption ability at the top of the area.

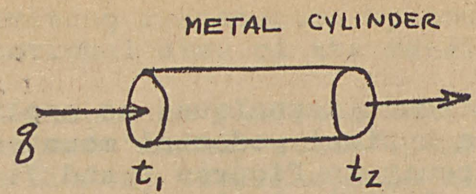
Forced air cooling will in general greatly increase the efficiency of heat transfer and is widely used to obtain efficient heat transfer in electronic equipment. For obvious reasons, its use in CATV is limited to headend equipment or in special situations.

RADIATION

When a body radiates, it transmits energy without the necessity of a medium in the same manner as radio waves. Thermal radiations are emitted by all matter unless at absolute temperature. This energy is absorbed by other matter and reconverted into heat. When the rate of absorption exceeds the rate the receiver emits, then it is a net transfer of radiant energy and unless the heat is removed by some means, the temperature of the receiver will rise.

In CATV environment solar radiation and the absorption of it is a very important consideration. This radiation level has been measured at approximately 250 BTU/hours per square foot at noon on a typical clear and sunny summer day. Where poor thermal conductivity or convection conditions limit cooling by other means, radiation may be a vital part of the heat transfer mechanism from electronic equipment to the atmosphere.

Radiation from a black body follows the low $q = uT^4$. Where T is absolute temperature of the body, u is a constant. The black body is the most efficient radiator and absorber. For surfaces other than black, only a fraction of the maximum energy will be radiated or absorbed. A fractional coefficient, the emissivity, is used to account for the relative efficiency of the material. Values of this coefficient have been measured for many materials and are recorded in literature.



q HEAT FLOW RATE

K THERMAL CONDUCTIVITY

A CROSS SECTION AREA

R THERMAL RESISTANCE OF CYLINDER

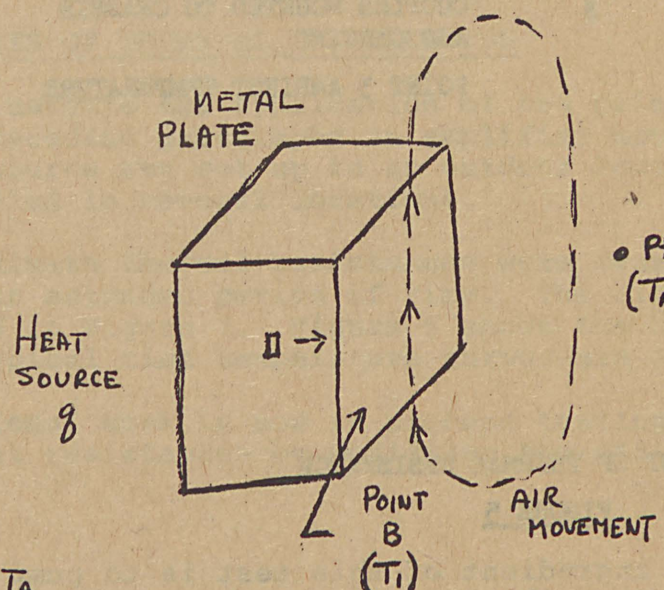
$$q = k\frac{A}{L}(t_1 - t_2)$$

$$q = \frac{t_1 - t_2}{R} \qquad R = \frac{L}{kA}$$

$$i = \frac{E_1 - E_2}{R}$$ (ANALAGOUS ELECT. CIRCUIT)

HEAT FLOW BY CONDUCTION

<u>FIGURE 3</u>



POINT A IS A POINT AT AMBIENT AIR TEMPERATURE

R IS THE THERMAL RESISTANCE BETWEEN THE METAL BLOCK AND AMBIENT AIR

$$R = \frac{T_1 - T_A}{q}$$

$$T_1 - T_A = R \times q$$

HEAT TRANSFER BY CONVECTION

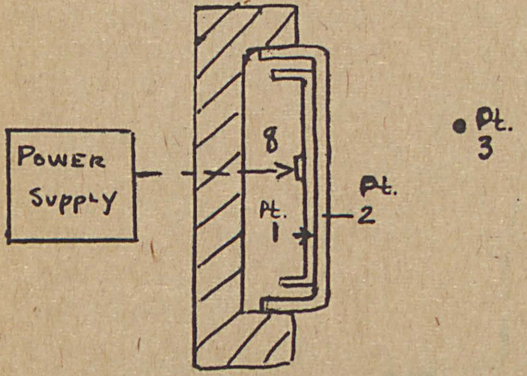
<u>FIGURE 4</u>

ANALYSIS OF THERMAL CIRCUIT

To illustrate the use of equivalent circuit technique, as applied to thermal circuits, I have sketched a typical pedestal mounted amplifier along with an equivalent circuit in Figures 6 and 7. It can be seen from this that like an electrical circuit, a thermal circuit can get quite complicated. However, as in electrical circuit analysis, one can simplify the circuit by neglecting those items which are not likely to cause serious errors. In order to do this one needs to be able to estimate the magnitude of the thermal resistance at the interface in question. This can be done most easily by making temperature rise measurements, however, in many cases involving conduction one can calculate the resistances from the resistivity (conductivity) information in the literature.

A discussion of how to measure thermal resistance can be helpful in understanding this concept.

Figure 5 shows a technicque for measuring the thermal resistance through an amplifier casting.



q CONTROLLED HEAT SOURCE

POINTS 1 & 2 ARE THERMOCOUPLES MOUNTED TO CHASSIS AND CASTING

POINT 3 AMBIENT TEMPERATURE

$$R(1-2) = \frac{t_1 - t_2}{q}$$

$$R(1-3) = \frac{t_1 - t_3}{q}$$

MEASUREMENT OF THERMAL RESISTANCE

FIGURE 5

Note that the necessary ingredient of this test is to pump a known amount of heat through the interface and measure the temperature rise across it. It is not necessary to understand mechanism of actual heat transfer since the thermal resistance gives a coupling coefficient, which relates to the total heat transfer however it occurs. Of course, it is also possible (and in many cases more practical) to measure temperature drops under actual conditions and estimate the limiting thermal resistance. The next step involves attempting to reduce these limiting resistances by some means such as increasing the cross sectional area of the metal contact to bridge an air gap.

It should be realized that the discussion up to this point has assumed "steady state" condition. By this it is meant that sufficient time has been allowed for the thermal losses to balance out. All materials require a finite quantity of heat (watts for a definite time•period) to raise their temperature a fixed number of degrees. This property is analogous to capacity in an electrical circuit and depends on the mass of the material, as well as the intrinsic properties of the material. The term "specific heat" is used to describe the thermal capacity of the material and the relationship which can be used to calculate time lag is shown below. A constant heat flow is assumed.

$$\text{TIME} = \frac{\text{(SPECIFIC HEAT) (MASS)}\Delta\text{T}}{\text{WATTS}}$$

The analogous relation for an electrical circuit is

$$\text{TIME} = \frac{Ce}{i} \qquad \frac{\text{(CAPAC) VOLTAGE}}{\text{CURRENT}}$$

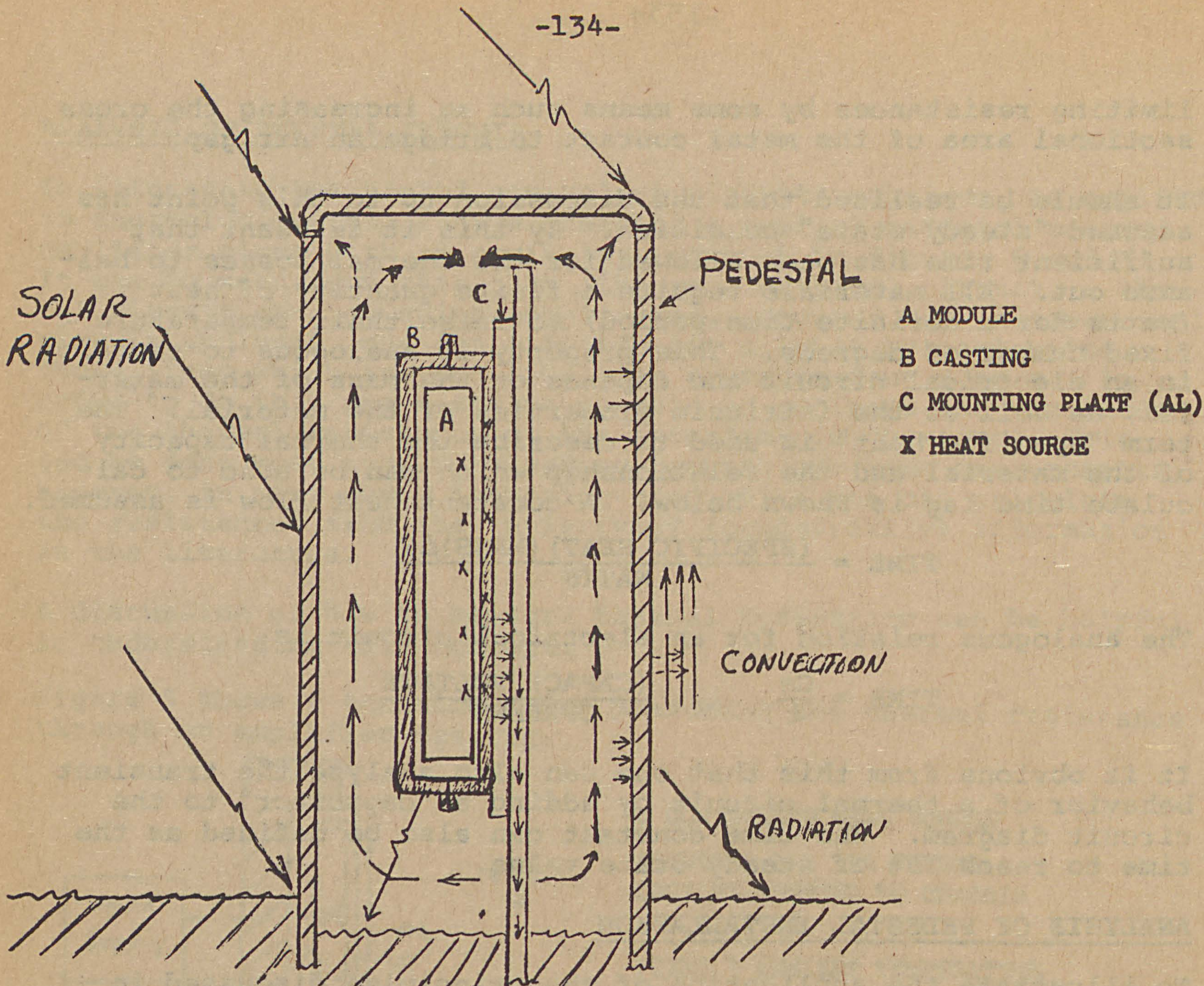
It is obvious from this that one can also analyze the transient behavior of a thermal circuit by adding a "capacitor" to the circuit diagram. The time constant can also be defined as the time to reach 70% of steady state value.

ANALYSIS OF PEDESTAL INSTALLATION

To illustrate the application of the principles discussed in the preceding paragraphs an amplifier housing with an internal heat source was set up in an outdoor location with thermocouples installed in several locations.

Approximate thermal resistances were measured and tests were run over an extended period of time. The circuit diagram is presented in Figure 7. Figure 6 shows the heat transfer interfaces and typical time temperature curves are shown in Figure 8.

Additional work is now in process testing methods of reducing thermal resistances by modifying the pedestal.



NOTES:

1. PEDESTAL IS SEALED EXCEPT FOR SEAMS AT TOP AND SIDES. AIR MOVEMENT INSIDE IS SEVERELY LIMITED.
2. PEDESTAL DIMENSION ABOVE GROUND 10.5" x 10.5" x 32"

   TOP AREA APPROXIMATELY .77 SQUARE FEET

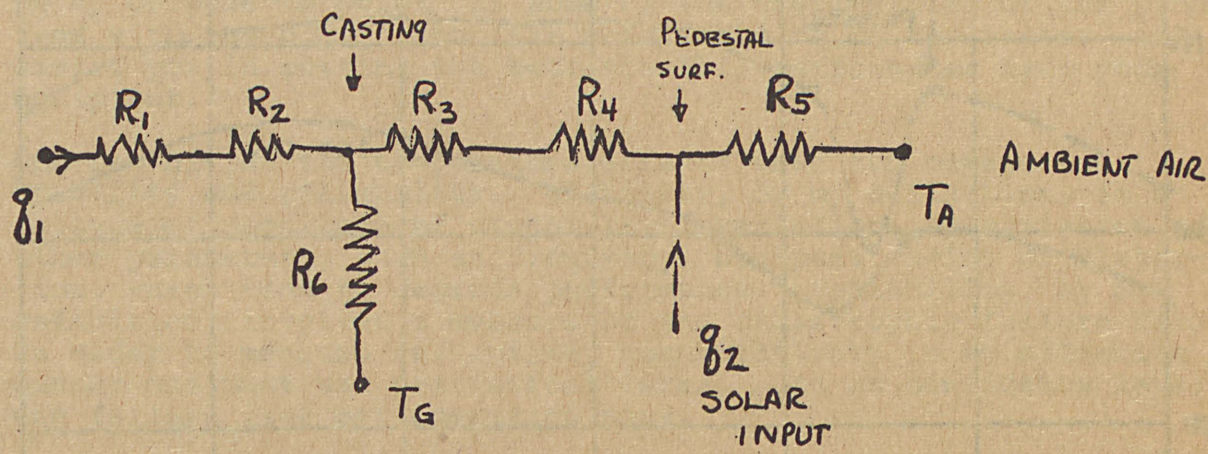
   SIDE AREAS APPROXIMATELY 2.3 SQUARE FEET
3. PEDESTAL MATERIAL:

   STEEL DARK GREEN PAINT, 3/32 THICK, ABSORPTIVITY APPROXIMATELY .73
4. ALUMINUM CASTING:

   APPROXIMATELY 7.5" x 16" x 4", APPROXIMATE AREA 2.7 SQUARE FEET

HEAT TRANSFER IN PEDESTAL

FIGURE 6



R_1 HEAT SOURCE TO INTERNAL MODULE

R_2 MODULE TO CASTING

R_3 CASTING TO INTERNAL AIR

R_4 INTERNAL AIR TO PEDESTAL

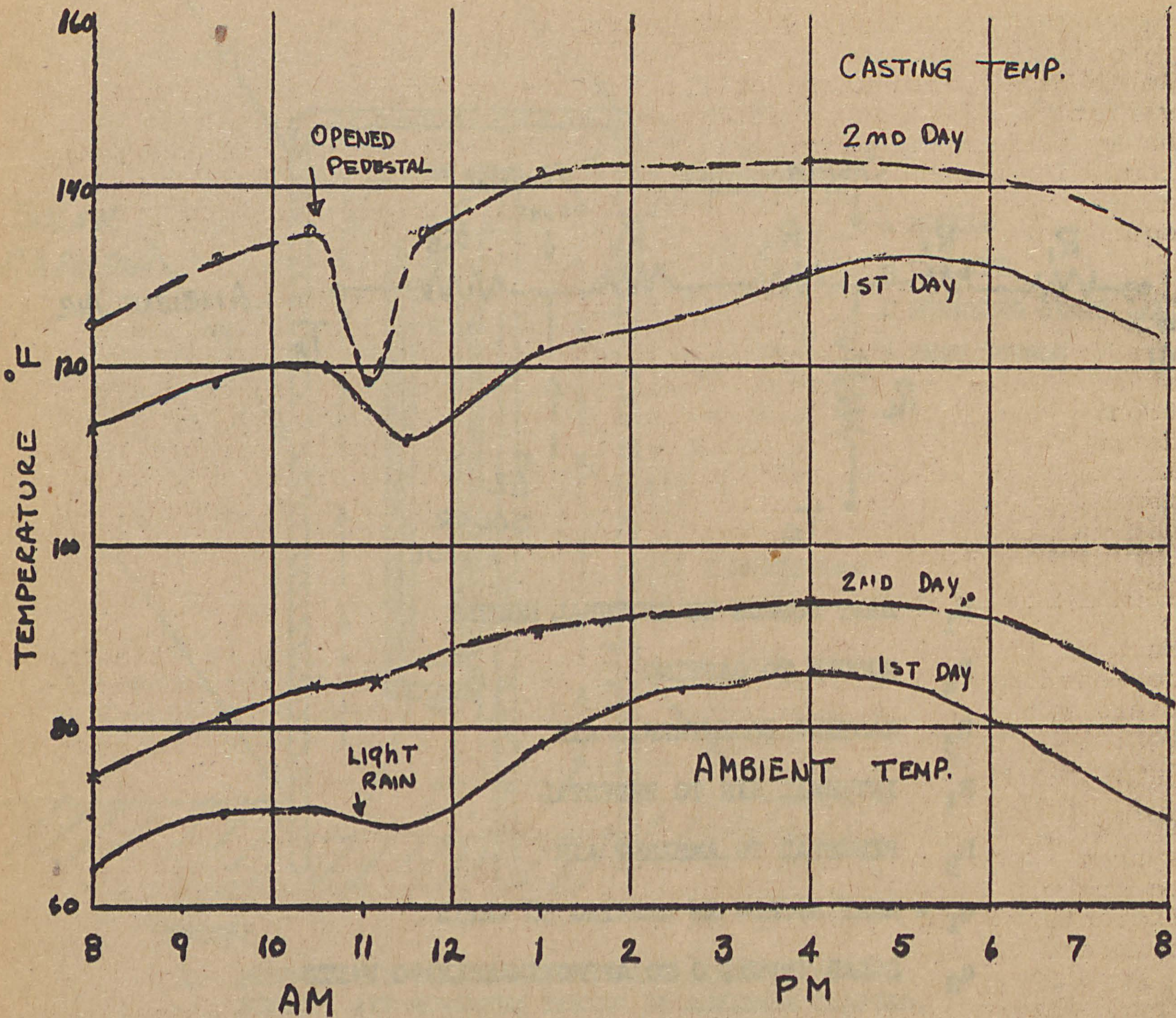
R_5 PEDESTAL TO AMBIENT AIR

q_1 = HEAT SOURCE IN CASTING 58 WATTS

q_2 SOLAR INPUT, 0 TO APPROXIMATELY 40 WATTS

EQUIVALENT THERMAL CIRCUIT
PEDESTAL INSTALLATION

FIGURE 7



TEMPERATURE TESTS ON PEDESTAL INSTALLATION

FIGURE 8

TEMPERATURE EFFECTS ON CATV SYSTEM

An in-depth discussion of the effects of ambient temperature variation will not be attempted in this paper. Instead it will be my purpose to point out some of the complexities of the problems with the conviction that understanding of the basics will assist you in getting the best possible performance from your equipment.

One can divide the temperature effects into two categories: stability and reliability. Stability, by my definition, is a measure of magnitude of signal level variations or variation of other parameters, such as frequency, bandpass, noise or distortion, which tend to degrade performance. Reliability, by my definition, involves a measure of the catastrophic failure rate. In order to measure reliability quantitatively in an effective manner one must use statistical terms, such as confidence level and failure rate per operating hour.

TEMPERATURE STABILITY

Much of the technical discussion on system stability to date has centered around the effectiveness of ALC systems in trunk amplifiers with the implication that "cable loss versus temperature" follows precise rules over wide temperature ranges and the complete frequency spectrum.

It is my belief that we must direct our attention to the complete system - headend equipment, cable and amplifiers. We need also to concern ourselves with precise behavior of temperature coefficients at high and low temperature extremes and over the complete bandpass.

For instance, our measurements on coaxial cable loss versus temperature indicate rather peculiar behavior at temperatures below 30° F. Certainly more actual test data must be made available on this important system component. It would not be unusual to find that temperature coefficient of cable is frequency selective or varies non-linearly with operating temperature. An investigation of other components, such as resistors, capacitors, transistors and other electronic components, shows that temperature coefficients very often vary in an unexpected manner. Consider the following examples taken from manufacturers' literature.

1. Carbon resistors increase in value with both increasing and decreasing temperature about a 25° C nominal temperature.

2. Ceramic capacitors may have a temperature coefficient which varies by a factor of 2;1 over the temperature range of zero to +40 C. There is also substantial variation for different types of dielectrics.

3. Electrolytic capacitors typically show negligible change in impedance for temperatures 25° C to 85° C, while in the range +25° C to -20° C the impedance will increase by 50% (50% decrease in capacitance).

With regard to headend equipment, it is of course true that this equipment need not withstand wide temperature variations. On the other hand, it is also true that this equipment is often not as carefully designed as the distribution amplifier and tends to be more sensitive to temperature because of the narrow band characteristics of the circuitry. I am afraid that the stability problem with this equipment is often accentuated by poor installation techniques in the rack mounting. A little air circulation and more careful distribution of heat sources will often help.

RELIABILITY VERSUS TEMPERATURE

Any one who has been involved in CATV for any length of time has had some direct experience with the adverse effect of high temperatures on the reliability of CATV equipment. The average CATV system includes tens of thousands of electronic components and each of these is subject to a predicted failure rate, which is directly dependent on operating electrical parameters and its ambient temperature. A quick review of some published data derived from component testing will illustrate this point.

CARBON RESISTORS	MIL R-11 quotes a failure rate at 50% of rated wattage, .018% per 1000 hours at 20° C and .03% per 1000 hours at 70° C at confidence level of 60%.
FILM TYPE RESISTORS	MIL R-10509 quotes .04% per 1000 hours at 20° C and .08% per 1000 hours at 70° C at confidence level of 60%.
SEMI-CONDUCTORS	Typical data taken from manufacturers' published information predicts an increase in failure rate by 2.5 times, if junction temperature is increased from 80° to 100° C.
ELECTROLYTIC CAPACITORS	Typical data shows the predicted failure rate is reduced by 50% when the temperature is reduced from 85° C to 75° C.

I have purposely omitted absolute failure rate numbers from the discussion in order not to imply that the data is directly applicable to CATV equipment. In practice the designer has the ability to derate most components to reduce failure rates to very small value. Another problem, which is difficult to cope with is the fact that the "failure" as defined for the test data may have little relation to the CATV application. Nevertheless, any such tests which could be devised from CATV equipment would show a correlation between temperature and failure rates.

In our quest for the best possible reliability, it is important that temperature extremes be minimized with good design and installation. The large numbers of components involved in a CATV system mean that highly reliable components are a must.

Temperature fluctuations with the inherent mechanical and electrical stresses tend to "shake down" new equipment by showing up manufacturing defects or defective components which tend to fail within the first 100 hours of operation. Hence, a moderate number of failures in the early life of equipment may not represent a true picture of the typical expected long term failure rate of the system.

CONCLUSION

I have reviewed the basic concepts of heat transfer with the hope that this will lead to further study on your part. In addition I have attempted to point out the advantages of the use of a thermal circuit diagram in studying and analyzing heat transfer.

The discussion on the effects of temperature was included to point out the many areas which are affected by temperature and the caution that temperature coefficients are variable with operating temperature.

It is my contention that your inquisitive minds, coupled with temperature measuring instruments and ingenuity, will result in a measure of increased CATV performance.

In closing I would like to point out one additional fact. CATV equipment has a decided advantage over aerospace equipment in that extreme miniaturization is not an overriding consideration. With miniaturization invariably comes increased component density and along with it increased thermal density and very special heat transfer problems to maintain reliability. Equipment users will do well to keep this in mind.

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