A Preliminary Model for High-Power Waveguide Arcing and Arc Protection

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This is the first article in a series describing the ongoing effort of the Transmitter Group to upgrade the arc protection subsystems that are, or will be, implemented in the DSN high-power transmitters. This article reviews the status of our present knowledge about waveguide arcs in terms of a simple engineering model and discusses a fairly general arc detection scheme. Areas where further studies are needed are pointed out along with our proposed approaches to the solutions of these problems.

I. Introduction

This is the initial report on one phase of the ongoing effort of the Transmitter Group to upgrade the arc protection subsystems currently used in the DSN high-power transmitters. The ultimate goal of this effort is to develop, with a known margin of safety, an extremely fast and highly reliable arc protection system which can be designed, manufactured and implemented for the eventual automation of these transmitter subsystems.

High-power microwave breakdown invariably results in arcing inside a nitrogen-filled waveguide system ($P \sim 1$ atm). The breakdown and subsequent arc formation interrupts the normal high-power transmission and causes a very large standing wave to be set up between the microwave source and the arc. Such high-level standing waves can be quite destructive to the components employed in the high-power transmission if their peak power ratings are exceeded. In addition, the accompanying arc once formed was found always moving toward the source at a speed depending on the field level (Refs. 1,2,3). Such high-power arcs can cause new or additional damages through their heating and thermal shocking effects as they propagate through the system. Often the arc damage is of a very severe nature. As an example, if the arc is allowed to travel to reach the output window of a high-power klystron amplifier before the klystron output can be turned off, the arc literally hangs up at the window and destroys it, which usually leads to a costly destruction of the klystron amplifier itself.

Even though precautions can be taken to reduce the chance of microwave breakdown within the designed power rating when assembling the transmission system (Refs. 4, 5), a complete prevention can never be assured. To protect system components against damages in the event of breakdown, protective devices must be employed. Protection is accomplished by removing or reducing the microwave energy that feeds the breakdown within a very short period of time after the breakdown is detected. For a klystron amplifier, this can be the turning off or drastic reduction in the klystron drive. Since the energy level required to sustain an arc is much smaller than that to initiate one, once an arc is initiated, the klystron output must be well attenuated to completely extinguish the arc.

The arc and the arc plasma cause high reflected power during their formation and propagation (Refs. 1,2,3). A reverse power detector, properly located, is a highly satisfactory device for arc detection. However, the reverse power detector doesn't provide protection against arcs formed between the reverse power detector (directional coupler) and the source – the most damaging kind. For a positive arc protection, other types of devices such as light-sensitive ones have to be used in this region, preferably with one device viewing the klystron output window directly.

In the following, we will concern outselves mainly with the protection of the output window against arc damage, as arcs formed elsewhere can be easily detected by monitoring the reverse power. A simple model showing the energy relationship associated with microwave arcing and a general optical detection scheme is discussed. Due to the complexity of the process and lack of applicable experimental data, only a semiempirical discussion is attempted at the present time. This article will briefly review the status of our present knowledge about microwave arcing inside a high-power waveguide system; at the same time it will also point out the areas where further theoretical and experimental studies are needed as well as our proposed approaches to the solutions of these problems.

II. Arc Model

Radiations emitted by nitrogen arc plasma have been actively studied both experimentally and theoretically (Refs. 6,7). Because of the complexity of the arcing process, a general theoretical treatment is impossible. Often, simplifying assumptions such as local thermodynamical equilibrium, the arc thermal-chemical state, arc parameters (pressure, temperature, current density, radius, symmetry, etc.) and radiation wavelength range have to be made to facilitate the calculations of both line and continuum radiations. Experimentally, the arc plasma has to be stabilized and stationary for data collection. Obviously the applicability of the results from these studies to the case of waveguide arcing during high-power transmission is not without question, because the latter is essentially a time-dependent discharge phenomenon. As shown in these studies, arc plasma radiation depends strongly on the thermal-chemical state of the plasma, which in turn varies considerably with the degree of departure from equilibrium. To make the matter more uncertain, these studies often show some degree of discrepancy among themselves regarding the interpretation of experimental results. Nevertheless, they do provide us an important means to understand arc radiation on a microscopic level. The model given below will be based on macroscopic processes for a first-order characterization of the waveguide arc, however. The reason is that the macroscopic characteristics are only partially understood so far, and a complete knowledge is needed for any meaningful study of the underlying microscopic processes.

According to the law of energy conservation, the energy relationship right before and after the waveguide arcing can be represented by the block diagram in Fig. 1.

Experimentally, the characteristic time for complete arc formation has been found to be of the order of a few microseconds. Conceivably, this time must be a function of the power level. Unfortunately, to our knowledge, this functional dependence has not been systematically examined to date. It turns out that the arc protection also has to be accomplished within approximately the same period of time after initial arcing is detected in order to avoid any real damage (Refs. 1,8). This microsecond response time is one of the important design parameters for an arc detector. The arc shape based on the field profile (TE_{10} mode) would be a cylinder with an approximately elliptical cross section. The actual shape has not been reported previously, probably because of the difficulty of direct visual observation of waveguide arcs. In some experiments where continuous arc tracks were left behind, a spatial periodicity of half guide wavelength along the propagation direction can be seen, with the spatial extent in the cross-sectional plane being modulated. It seems possible to have simultaneous arcings at half guide wavelength apart after the initial arcing if the standing wave field exceeds the breakdown field. This possibility has not, to our knowledge, been explicitly stated or observed in the existing literature.

Once fully formed, the arc plasma becomes a very effective shorting plane despite its limited extension in space, as evidenced by the presence of very little transmitted power and a very large amount of reverse power. Typically, the transmitted power is about 1 percent of the incident power, while the reverse power can range from 50 percent ($P_{inc} \simeq 20$ kW) to almost 98 percent ($P_{inc} \simeq 1$ MW) of the incident power (Refs. 1,2,8).

The difference between the incident and the reflected plus the transmitted power is the power associated with arcing (energy "absorbed" by the arc). Although not all of this energy is converted into radiation, it is believed that a substantial fraction is. A division of the energy according to the observable macroscopic phenomena is given in Fig. 2. Such division is somewhat simplified and not without ambiguity. It is done here for the purpose of identifying major phenomena which might offer a potential for arc detection. A brief discussion of each category is given as follows:

(1) Sonic wave (pressure wave) is produced along with the

breakdown. At high power level, the sonic wave becomes loud enough to be audible, and often causes the waveguide to shake. It is created in a short burst as breakdown is initiated. Conceivably we can use acoustic transducers to pick up such sonic wave as an indirect indication of arcing. Signals are then processed to activate the protection mechanism. But in view of the requirement on the device sensitivity, stability, response time, power supply and noise immunity, this method seems at best a supplementary one.

(2) Owing to its surface resistance, the waveguide temperature is elevated during power transmission. At equilibrium, the temperature is stabilized and the gas inside will also come to equilibrium at this temperature. Because of the reduction in gas dielectric strength at higher temperature for a given pressure, the maximum power handling capability of the waveguide system is lowered. If a breakdown is suddenly initiated at a certain point, additional heat is imparted to the gas molecules surrounding that point, with the effect of reducing local dielectric strength even further. With the incident power maintained at the same level, it is clear that a catastrophic chain breakdown can be triggered. This is one of the mechanisms that explains the arc movement toward the source. One way to increase the threshold of arcing is to provide sufficient cooling capability to the waveguide system to remove the dissipated heat and to prevent formation of hot spots, thus preserving the maximum power rating. The other would be to increase the gas pressure, which is limited by the strength of the window material and the tolerable leakage rate only.

(3) The waveguide wall heating discussed here is the additional heating due to the presence of arcs. During arcing, part of the energy is deposited in the waveguide wall in the form of heat through the bombardment of energetic electrons and ions. For a prolonged arcing, the local temperature rise in the waveguide can be such that the wall material becomes melted. The turbulent nature of arcing can eject small masses of the molten material into the waveguide. These ejected masses are not directly thermally anchored and get heated up very rapidly, causing more arcings because of the reduced dielectric strength and local field enhancement around these masses. This situation is known as massive breakdown and fortunately is more likely to happen at much higher power levels. In any event, arcs once initiated have to be quenched as soon as possible to avoid any prolonged arcing and its extensive damage.

(4) The remaining part of the energy is distributed among various atomic and molecular processes such as dissociation, ionization, reattachment, recombination or even chemical reaction with wall material. Some of them are radiative, and the others are nonradiative, depending on whether photons are released as a product of the process. The radiation emitted consists of line spectrum and continuum. Because the arc is in a highly complex state with many chemical species, reabsorption of the emission is not negligible, especially for the line spectrum. Therefore, what we are interested in is the total amount of energy of the net emission coming out of the arcing region and how it is spectrally distributed. Such information for waveguide arcs is rather incomplete and is very difficult to obtain due to its time-dependent and random nature. There exist some calculations of equilibrium nitrogen plasma radiation which agree more or less with experimental results (e.g., Ref. 6). As indicated before, the radiation characteristics depend strongly on the thermal-chemical state of the arc plasma. For example, for a difference in plasma temperature by a factor of 2 (say 7,000 and 14,000 K), calculations showed that the net emission per unit source volume per unit solid angle can differ by more than 3 orders of magnitude. Moreover, these calculations covered only a very limited range of radiation spectrum while experimental observations seemed to indicate a much broader spectral distribution, probably ranging from UV to low frequency RF. Thus it shows the need that more data pertinent to the real arcs have to be gathered experimentally.

In order to overcome this inherent difficulty of measuring time-dependent arc properties, we plan to carry out measurements on a sustained arc inside a resonant section of a waveguide system. This scheme will not only provide us a more or less stable source but needs only $1/Q$ of the power to maintain the same level inside the resonant section, where Q is the loaded quality factor of the resonant section. This should solve the dilemma of trying to initiate an arc on one hand and on the other, to protect the klystron amplifier at the same time. Both the total radiation intensity and the spectral distribution from the sustained arc will be measured. The spectral range covered will be determined by the measuring instrument. With known arc geometry, detector sensitivity and the relative orientation of the arc and the detector, a normalized arc emission characteristic can be obtained. Such a controlled experimental arc probably is a good approximation to an arc hanging at the klystron output window and is expected to less resemble a moving arc. The variable parameters in this study would be incident power level, gas pressure, gas temperature, arc geometry and pulse length. With slight modification, the arc formation time, the arc energy absorption and arc traveling speed can also be measured. Detail experimental considerations, arrangements and results will be presented in the future.

III. Arc Detection

With the characteristics of waveguide arcs approximately known, we could then proceed to design a detection system with certain predictable performance. Because the detected arc radiation is eventually converted back to electrical energy for control purposes, a fairly general detection scheme can be outlined as shown in Fig. 3. In addition to the direct arc emissions and those indirectly scattered into the optical entrance aperture, there are also ambient light leakage and output window glow. The ambient light can, in principle, be reduced to an insignificant level by properly arranging and shielding the microwave components. The window glow on the other hand presents potentially a more serious noise source. The glow is a consequence of the dissipation in the output window under normal high power transmission; i.e., it is an integral part of the power transmission process. Its exact nature has not been carefully examined so far, and its effect on the arc detector can only be speculated at this time. Our study will look into this problem to determine its seriousness and will recommend remedies, if needed, such as better cooling of the window or designing a frequency-sensitive detector which will ignore the glow.

Upon entering the aperture, not all the light is transmitted due to the Fresnel reflection if there is a difference in the indices of refraction across the interface (typically 5 percent). Furthermore, if optical fiber is used for transmitting the light signal over some distance, only those beams with incident angle less than a certain acceptance angle will be launched into propagating modes of the optical fiber.

If we define $J_1\ (\nu,\vec{\gamma})$ as the spectral density at frequency ν of arc emission per unit volume per unit solid angle at arc spatial coordinates $\vec{\gamma}$, then

$$J_1(\nu) \equiv \int_{\substack{volume \\ \Omega(\theta<\theta_a)}} J_1(\nu,\vec{\gamma})\, dV d\Omega \qquad (1)$$

is the spectral density of the direct arc emission entering the entrance aperture that will propagate inside the optical fiber guide, where the solid angle Ω is subtended by the entrance aperture toward the arc. Similarly, we can define $J_2(\nu)$, $J_3(\nu)$ and $J_4(\nu)$ for the indirectly scattered arc emission, the ambient light leakage and the window glow respectively.

Furthermore, we will define the following quantities:

$F(n_1,n_2)$ = fraction of Fresnel reflection loss, where n_1 and n_2 are the indices of refraction for the two adjacent media across which the light is transmitted.

$T(\nu)$ = transmittance of the optical fiber guide

$P(\nu)$ = transfer function of the optical signal processing

$R(\nu)$ = responsitivity of the optical transducer, (A/W)

Then the optical detector partial electric current output due to the arc light input at the entrance aperture is

$$\begin{aligned} I = \int & [J_1(\nu) + J_2(\nu) + J_3(\nu) \\ & + J_4(\nu)]\ [1-F(n_1,n_2)]\ T(\nu)\, P(\nu)\, R(\nu)\, d\nu \qquad (2) \\ \equiv\ & I_1 + I_2 + I_3 + I_4 \end{aligned}$$

where signal current comes from direct and indirect arc emissions $(I_1 + I_2)$.

The total current of the optical transducer is

$$\begin{aligned} I_{total} &= I + I_N \\ &\equiv (I_1 + I_2) + (I_3 + I_4 + I_N) \qquad (3) \end{aligned}$$

where I_N is the noise current of the optical transducer. A substantial fraction of the noise current comes from the temperature-sensitive dark current of the detector.

The signal to noise ratio (SNR) at this point is

$$\left(\frac{S}{N}\right)^2 = \frac{(I_1 + I_2)^2}{I_3{}^2 + I_4{}^2 + I_N{}^2} \approx \frac{(I_1 + I_2)^2}{I_4{}^2 + I_N{}^2} \qquad (4)$$

if ambient light leakage is negligible.

The magnitude of this required input SNR is an important design parameter to be determined. The final SNR at the output of the threshold logic circuit depends, of course, on the electrical components used and should be maximized despite the presence of power supply ripple, EMI, and thermal drift. Its magnitude will be determined based on the required signal level, detection probability and acceptable false alarm rate.

In reality, there are additional losses in the optical path when connections have to be made. A general rule of thumb here is that about 2-3 dB/connector and 0.1 dB/splice loss are present. For each step of optical path, ambient light leakage is also always present. We have assumed they can be minimized to be negligible. Typical fiber transmittance over the visible and IR spectrum is about 3 dB for a length of 0.5 m. Additional fiber input coupling losses may be necessary in order to isolate the optical transducer from being exposed to intense RF. The dielectric fiber may be advantageous in overcoming ground loop problems in the detection circuit, however.

The eventual total current output is limited by the spectral range over which the transducer has appreciable responsitivity. The commonly used optical transducers are pin photodiode, avalanche diode and photomultiplier tube. The first two are solid-state devices which require a bias of about 20 and 200 volts respectively. The photomultiplier tube is rather bulky and requires more than 1 kV supply. Our experimental study will primarily concern solid-state devices because, in parallel to this study, we will also evaluate a commercial arc detector based on photomultiplier tube. Solid-state devices seem to have adequate sensitivity and response time for arc detection. But their dark currents tend to increase rather rapidly with increasing temperature, thus changing the operation point of the arc detector. Often this thermal drift is large enough to cause false activation of arc protection and to saturate the arc detector. These have been the major problems encountered in the present arc detectors. The increase in the dark current as a function of temperature is inherent to the semiconductor p-n junction inside the diode and, therefore, the solution is either to maintain the diode temperature, or to compensate the thermal drift or to use ac coupling and/or high-pass filtering for the signal and noise.

The output voltage originated from the optical transducer is then compared to a reference voltage to produce a logic output. The threshold is determined by the amount of light output expected from an arc as well as the safety margin for noise and thermal drift. One way to increase the detector sensitivity is to increase the load impedance of the optical transducer as much as possible. However, the most important consideration here is to make sure that the time delay between the arcing and the logic pulse output is less than a few microseconds for a safe arc protection. This may have to be done at slight expense of the detector sensitivity and SNR.

IV. Conclusions

We have briefly discussed the waveguide arc according to a simple model based on an engineering viewpoint and outlined a general scheme for achieving protection against arc damage. Several questions have been raised concerning the waveguide arc characteristics and the arc protection that we plan to answer both experimentally and theoretically as soon as possible so that a reliable arc protection system becomes available not only to presently attended transmitter subsystems but also to unattended ones in the future as well.

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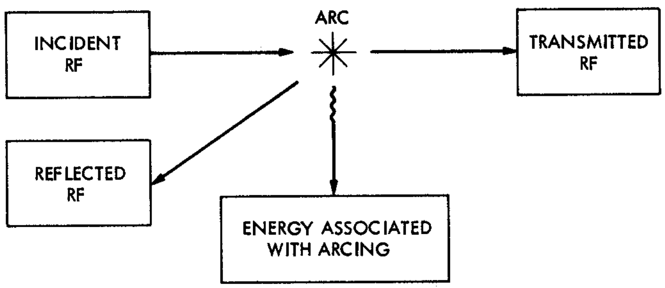

Fig. 1. Waveguide arc energy relationship diagram

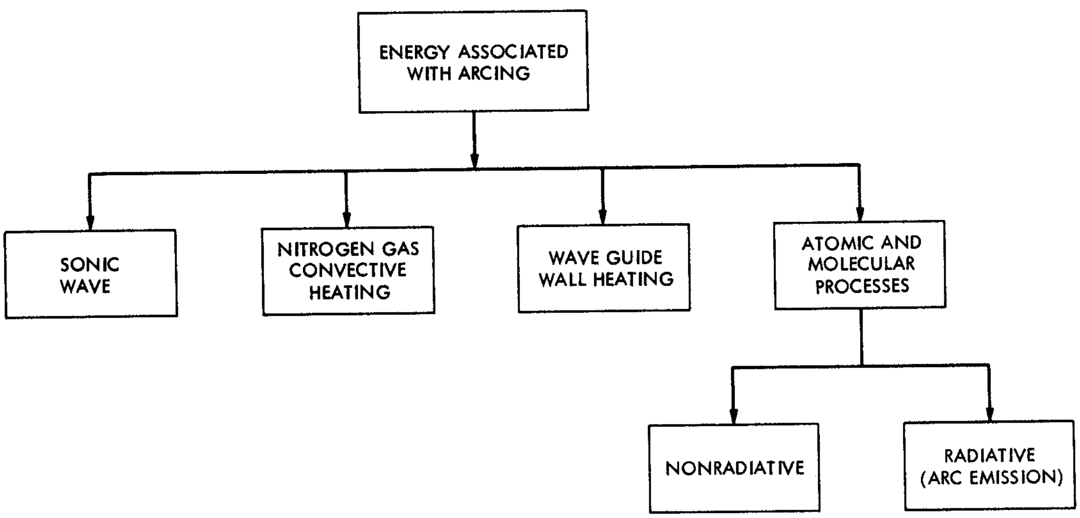

Fig. 2. Waveguide arc macroscopic energy division

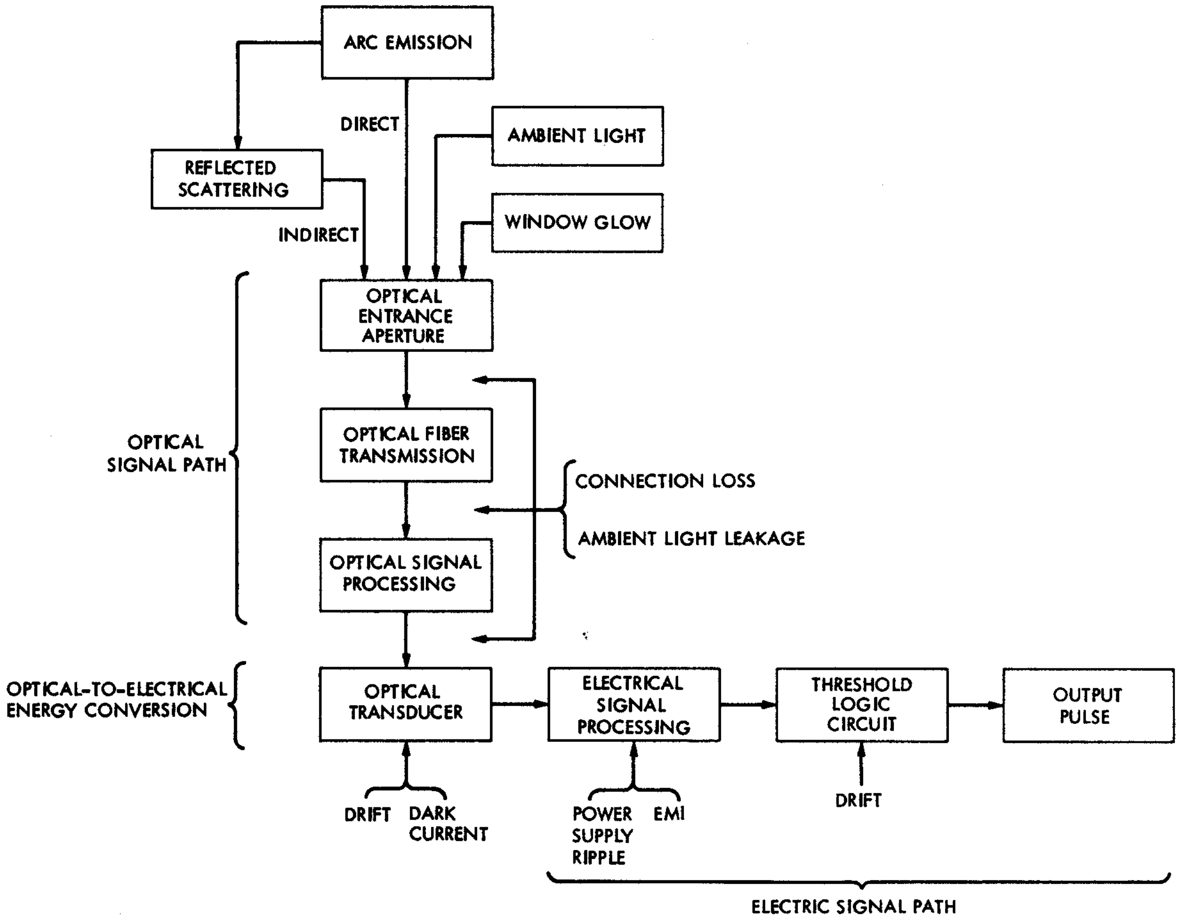

Fig. 3. A general scheme for waveguide arc detection