ELECTRONIC RADIATION IN THE VICINITY OF SYNCHRONOUS ORBIT SATELLITES: Literature Search

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A categorized list of representative references are presented that apply to the task of estimating and predicting undesirable radiation incident to a satellite in synchronous orbit. The categories of references address basic elements of the task. That is, some references apply to estimating the particle and field environment about the satellite and other references are relevant to estimating the behavior of the medium, either as supporting of electrical discharge or the excitation of radiation.

### KEY WORDS

- Breakdown
- Discharge currents
- Unstable plasma
- Satellite charging
- Magnetosphere synchronous orbit
through instability and/or the presence of plasma boundaries. Both theoretical and experimental references are included in each category where possible.

The breakdown of Plasma, which is a necessary condition to the generation of discharge currents in plasma, is a much studied phenomenon both theoretically and experimentally. The references 6a of this report, together with the bibliographies associated with each reference, provide a representative information base to support either a critical review of important elements of breakdown and electrical discharge literature from about 1960 to the present time, or an ordered resume of breakdown characteristics as determined in that time period.
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1. INTRODUCTION

A satellite at synchronous altitude acquires a charge, sometimes of extreme magnitude, which can adversely affect on-board electronics by subjecting them to large electromagnetic stress. A possible source of such undesirable radiation, for example, can originate from the power coupled from breakdown currents flowing near the satellite. Another potential source of disruptive radiation occurs if the charged satellite excites an unstable plasma to radiate from the plasma interior or boundaries. Instability can possibly produce a turbulent wake with associated noisy radiation. Though all these mechanisms are possible sources of undesirable radiation, emphasis is initially placed on discharge phenomena.

It is important to develop realistic estimates of the levels of radiation associated with the satellite motion through the complex and variable magnetospheric plasma. Plasma behavior is modelled by equations that contain defining plasma parameters and a number of characteristic terms. The more complex the plasma model, the more difficult is the solution of the plasma equations. Realistic calculations should use the simplest plasma models that adequately predict discharge currents and/or waves excited in unstable plasma.

This report begins the task of generating realistic estimates of satellite radiation levels and is concerned mainly with acquiring and
categorizing a suitable information base. The report is intended to present a systematic approach and to exploit the present state of the art of plasma physics where possible and profitable. The accompanying literature search provides an overview of this many sided subject as it applies to the objectives of the investigation.

The mechanism responsible for disturbing radiations produced by a charged satellite's interaction with its plasma environment depends in one instance on the time dependent behavior of a plasma that changes due to external and/or self-consistent fields. In the other instance, radiation depends on the excitation of the complex plasma medium.

In the first case, it is required to know the initial conditions of the medium and to have models to describe behavior at later times. In the second case, it is required to know the dispersion characteristics of the medium and interaction criteria that determine the excitation of waves or oscillations in the body of the plasma or at boundaries.

In either case, the appropriate plasma model used to predict currents, or waves and oscillations can be generated by estimating certain plasma parameters (see Figure 2). These depend fundamentally on particle species, densities, energies, cross sections for various reactions and field strength.

The block diagram of Figure 1 displays the components of the plasma medium (ambient and satellite generated) that contribute to the total environment.
The literature search is organized into categories as displayed in Figure 1. The elements of Figure 1 are further discussed on Page 5.

It was judged useful to include an appendix to the report, in which the following items are given as additional information:

A. A list of defining plasma parameters in general use.
B. A block diagram displaying the relationship between plasma parameters that define a plasma model.

The literature search also includes a list of references related to the lightning discharge mechanism, because this familiar and much studied phenomenon has features that resemble those of the charged satellite:

- A charge separation mechanism powers discharges in each case.
- $E$ fields must become intense enough to break down the medium (ionize it) so that discharge currents can flow.
Figure I. Flow Chart Satellite Charging Literature Search
The categories 1 through 6 a, b displayed in Figure 1, identify independent areas of literature search that are "input" to the tasks of estimating radiation incident to a synchronous orbit satellite from external media. Before estimates of discharge current generated spectra or of waves and/or oscillations excited in unstable plasma can be attempted, a description of the plasma medium is necessary. Only then, can the synthesis of a suitable plasma model be initiated to generate the desired estimates and predictions in accordance with the state of the art plasma physics.

The categories 1, 2, 3, 4 determine the total plasma environment, and each category is a somewhat independent area of theoretical and experimental research. The symbols \( N_0, N_i, N_e, \overline{E}, \overline{H}, T_e, T_i, T_n \) are descriptive of the basic constitution of the medium (particle densities, energies and the interacting field environment). The relative magnitude of ambient particle fluxes is also an important determinant in Category 2 and is not shown in Figure 1. The other symbols are defined as follows:

\[
\begin{align*}
N_0 &= \text{number density of neutrals} \\
N_i &= \text{number density of ions} \\
N_e &= \text{number density of electrons} \\
\overline{E} &= \text{externally applied and self consistent fields} \\
\overline{H} &= \text{externally applied fields} \\
T_e &= \text{electron temperature} \\
T_i &= \text{ion temperature} \\
T_n &= \text{neutral temperature}
\end{align*}
\]

In the neighborhood of a synchronous satellite, the above items can be complex functions of position within a Debye length of a satellite surface where discharges must originate. Part of the task of estimating discharge currents, for example, is to introduce reasonable simplifications and approximate plasma models in regions sensitive to breakdown and lying within this sheath.
The Category 5 representative references address the task of estimating plasma parameters that are suitable to define plasma models. The plasma parameters are defined in Appendix A.

Category 6 includes references relevant to the task of selecting an appropriate plasma model sufficient for the objectives of interest. The definition of plasma models is given in Appendix B.

The references 6A apply to the task of estimating the $E$ field strength producing breakdown of plasma, the conductivity of the plasma and other conditions critical to discharge currents produced in the broken down plasma, as powered by the satellite induced charge separations. The references are chosen to deal with elements of analysis essential to estimating currents realistically and in the present state of the art of plasma physics.

The references 6B apply to waves and oscillation produced in unstable plasma.
Although discharge of a charged satellite can occur either through material breakdown within the satellite itself or by breakdown of the external medium, this literature search examines only the case of radiation produced in the external medium. Strong discharge currents require that the plasma be broken down (ionized by electron impact). Hence, the region of interest must contain sufficiently strong E fields. This limits the region of interest (in the case of discharge phenomena) to the plasma sheath enveloping satellite surfaces, because the fields are screened in regions beyond the sheath.

The plasma models must be sufficiently realistic to describe a plasma that is not quasi-neutral and also include the relevant inelastic, elastic and diffusion processes that determine the magnitude of breakdown E fields and the subsequent time dependent behavior of plasma. Other radiation mechanisms depending on plasma instability may not necessarily be confined to the plasma sheath or necessarily require that plasma be electrically broken down.

The initial conditions for the plasma in the sheath depend on the satellite charging process and possibly on its time dependent behavior in building up charge and E fields. The references 1.1-1.7 are concerned with this process. Reference 1.3 is particularly oriented toward formulating the basic physical and mathematical model of satellite charging.
The breakdown of plasma in the sheath can be investigated theoretically, leaving the initial conditions open, and using a suitable set of plasma equations (model). The magnitude of the minimum breakdown $E$ field depends to a large degree on the amount of easily ionizable material present. Thus, the products of the interaction of ambient particles with the satellite surfaces that produce neutral particles (e.g., neutrals reflected, $+$ions neutralized, outgassing, sputtering) are possibly critical to breakdown characteristics. Also relevant to breakdown are the changes in the medium produced by products of thrusting systems. A neutral system may produce easily ionized or attaching molecules. An ionized thrust beam (satellite generated) can clamp the satellite potential to some lower value manifested in plasma external to the sheath. These considerations are the subjects of references 3.1-3.4.

Because unusual chemical reactions can occur in the presence of the discharges, the references 4.1 and 4.2 are included. Of most interest is the possibility of negative ion formation and the effect on breakdown of low ion mobility compared to the mobility of electrons.

The references of Category 5 consider criteria in standard use to develop plasma models.

The references 6A are chosen as representative of those that are concerned with both theoretically oriented and applications oriented aspects of plasma behavior. The list of DDC reports on Electrical Arc and Plasma contains a mix of theoretical and experimental investigations of breakdown.
behavior of plasma. Similarly, a theoretical and experimental mix can be found on more general plasma subjects in references 6A6-6A12. The reference 6A16 is of practical interest, as it parameterizes the cross sections of inelastic reactions (exciting, ionizing) through a "Maxwellian Model". A similar approximate modelling of reactions in the collision integral may be sufficient for the breakdown investigations of interest.

The references 6B, dealing with instability are chosen to be representative. Reference 6B1, which has also been cited elsewhere, presents an extensive bibliography. Once the appropriate plasma model is determined (refer to Figure 2 in the Appendix) it is expected that a considerable narrowing of the field of relevant references can be readily effected.

The references 6B3 and 6B4 examine the dispersion expressions using linear theory. Other references seem to establish the ability of linear theory to predict stability, though non-linear theory (refer to 6A21) is needed to describe the unstable behavior. The references 6B5 and 6B6 investigate the two general categories of plasma instability independently.

The possibility of a radiating turbulent wake developing should the plasma be unstable has been mentioned briefly in reference 1.3. The conjecture was applied to a satellite moving through the ionosphere. Whether this possibility is also applicable to the magnetospheric medium is perhaps even more conjectural. However, the references 6B7 and 6B8 on turbulence have been included as possibly relevant references.
1. Satellite Charging References

1.1 Interactions of Rapidly Moving Bodies in the Terrestrial Atmosphere, R.P. Chopra, Reviews of Modern Physics, April 1962.


   - Plasma Sheath and Screening Around a Rapidly Moving Body, E.H. Walker.

1.5 Probes in a Plasma from a Gas Dynamics View - Applications to Satellite Charging, Environmental Res. Papers, H.E. Moses, AFCRL-TR-76-0005 (continuum theory used vis-a-vis kinetic theory).


2.6 Synchronous Altitude Atlas, E.C. Whipple, University of California (This work is currently in progress.)


CHEMICAL REACTIONS UNDER PLASMA CONDITIONS (DISCHARGES)


PLASMA PARAMETER REFERENCES

REFERENCES RELEVANT TO PLASMA BREAKDOWN

6a.4 Motions of Ions and Electrons, W.P. Allis, TR 229, Res. Lab. Electronics, MIT.
6a.6 Advances in Plasma Physics, Volumes 1, 2, 3, A. Simon, W.B. Thompson, John Wiley and Sons, 1968.
6a.15 Basic Data of Plasma Physics, S.C. Brown, TR #2, Res. Lab Electr., MIT.
6a.20 DDC Reports on Electric Arc and Plasmas

AD- 727 799 20/9
STATE UNIV OF NEW YORK BUFFALO FACULTY OF ENGINEERING AND
APPLIED SCIENCES

DIAGNOSTICS ON STEADY-STATE CROSS-FLOW
ARCS, II: INFLUENCE OF VELOCITY AND CURRENT. (U)

DESCRIPTIVE NOTE: FINAL REPT.,
FEB 71 71P BENENSON,D. M. ICENKNER,A.

AD-A007 633 20/3 20/7
AEROSPACE RESEARCH LABS WRIGHT-PATTERSON AFB OHIO

AN INVESTIGATION OF COUPLED D.C. -
INDUCTION ARC DISCHARGES. (U)

DESCRIPTIVE NOTE: REPT. FOR JUL 72-JUL 73,
MAR 73 14P SCHREIBER,P. W. HUNTER,A. M. TAYLOR,P. IBENEDETTIO,K. R. 1

AD- 713 131 20/9 20/3
AEROSPACE RESEARCH LABS WRIGHT-PATTERSON AFB OHIO

SELECTED PAPERS PRESENTED AT THE HIGH-PRESSURE ARC
SYMPOSIUM SPONSORED BY THE AMERICAN PHYSICAL SOCIETY
ON 28 AND 29 OCTOBER 1979. (U)

DESCRIPTIVE NOTE: FINAL REPT.,
AUG 70 278P HUNTER,A. M. 1 II;

AD- 706 585 20/9 7/4
UPPSALA UNIV (SWEDEN) INST OF PHYSICS

PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON
IONIZATION PHENOMENA IN GASES (14TH) HELD AT
UPPSALA ON 17-21 AUGUST 1959, VOLUME I.

60 588P
CONTRACT: AF 61(052)-204

AD- 687 181 20/9
MOBIL RESEARCH AND DEVELOPMENT CORP PRINCETON N J CENTRAL
RESEARCH DIV LAB

BEAM PROBE MAPPING OF RAPIDLY FLUCTUATING PLASMA
DENSITY IN AN ENERGETIC ARC. (U)

DESCRIPTIVE NOTE: REPT. NO. 4 (FINAL), 1 DFC 67-30
AD—R21 435 20/9
ARNOLD ENGINEERING DEVELOPMENT CENTER ARNOLD AIR FORCE STATION TENN

PLASMA INSTABILITY OF A LOW PRESSURE ARC DISCHARGE WITH AN APPLIED LONGITUDINAL MAGNETIC FIELD. (U)

DESCRIPTIVE NOTE: TECHNICAL REPT. JUN 66-MAR 67; OCT 67 83P SHIPP, JOHN I.

AD—636 160 20/9 20/3 14/2
GENERAL ELECTRIC CO PHILADELPHIA PA MISSILE AND SPACE DIV

AN ANALYTICAL STUDY OF THE PHYSICAL PROCESSES IN THE CATHODE REGION OF AN ARC. (U)

DESCRIPTIVE NOTE: FINAL REPT., FEB 62-JUN 65; APR 66 127P LEE, T. H., GREENWOOD, ALLAN I.
BREINGAN, W. D., FULLERTON, H. P. I

DDC REPORT BIBLIOGRAPHY SEARCH CONTROL NO. BLJ45F

AD—750 478 20/9
STANFORD UNIV CALIF INST FOR PLASMA RESEARCH

LOW-FREQUENCY FLUTE INSTABILITIES OF A HOLLOW CATHODE ARC DISCHARGE: THEORY AND EXPERIMENT.

AD—750 477 20/9
STANFORD UNIV CALIF INST FOR PLASMA RESEARCH

LOW FREQUENCY INSTABILITIES IN INHOMOGENEOUS MAGNETOPLASMA. (U)

AD—749 552 20/9
VANDERBILT UNIV NASHVILLE TENN DEPT OF PHYSICS

ELECTRICALLY DRIVEN SHOCK PLASMAS. (U)

DESCRIPTIVE NOTE: FINAL SCIENTIFIC REPT. 1 SEP 71-31
AD-A019 793 20/9 20/7
Rensselaer Polytechnic Inst Troy NY Plasma Dynamics Lab

Current Density and Space Potential in Plasmas.

Descriptive Note: Final Rept. 1 Dec 74-30 Jun 75.

AD-739 939 20/9
Aerospace Research Labs Wright-Patterson AFB Ohio


Descriptive Note: Final Rept.

AD-A019 457 20/9 20/5 9/3
Office of Naval Research Arlington VA


Descriptive Note: Final Rept.

AD-731 803 20/9
Systems Research Labs Inc Dayton Ohio

Arc Motion and Modes in a Homopolar Device.

Descriptive Note: Final Rept. Sep 67-Aug 69.

AD-634 023 20/9
Aerobet-General Nucleonics San Ramon Calif

Research on Unstable Oscillations in Energetic Arcs.

Descriptive Note: Final Technical Rept. 1 Mar 65-30
ON AN EQUATION RELATED TO NONLINEAR SATURATION OF CONVECTION PHENOMENA

DESCRIPTIVE NOTE: TECHNICAL NOTE,
AUG 72 25P CAP, FERDINAND ILYASHINSKY

A TEST FOR THE VIABILITY OF FLUID CODES IN THE COLLISIONLESS REGIME

DESCRIPTIVE NOTE: INTERIM REPT., MAY 75 25P MAHEIMER, W. H. LIEBER, P.


This reference includes a critical review of the literature regarding the nonlinear effects of fields on a plasma medium. These affect transport properties of a plasma, including the conductivity. The latter is important in determining the subsequent behavior of broken down plasma subjected to E fields as in the boundary layer of a moving satellite.

REFERENCES ON INSTABILITY

6b.1 Handbook on Plasma Instabilities, F.P. Cap, Academic Press, 1976, Ch. 3, 9, 10, 11, 12, 13.

6b.2 Plasma Physics in Theory and Application, W.B. Kunkel, University of California, 1966, ch. 5, 8.

6b.3 Linearized Theory of Plasma Oscillations, L. Oster, Revs. of Mod. Physics, January 1960.

6b.4 The Dispersion Equation for Plasma Waves, N.G. Van Kampen, Physica XXIII, 1957.


REFERENCES ON
LIGHrNING THEORY


   Theory of Lightning, D.J. Malan, from above.

4. Recent Advances in Atmospheric Electricity, Proc. 2nd Conf. on Atmospheric Electricity, 1958.

5. Thunderstorm Electricity, University of Chicago Press, 1953.
3. CONCLUSION AND RECOMMENDATIONS

An initial review of the literature in the categories chosen for literature search reveal that all categories are much involved with various aspects of plasma physics. A critical review of the literature in each category then appears to be a logical next step. However, because the objectives are relatively narrow, requiring the estimation of radiation incident to a synchronous satellite, it is expected that the depth to which each category need be investigated, can be correspondingly moderated.

Assuming that radiation produced by discharge currents in external media is the most likely source of undesirable external radiation, suggests that analysis begin with the electrical breakdown of diffuse plasma. A plasma model which includes a set of expression for charge continuity, current or momentum density and energy balance and is descriptive of a suitable multi-component plasma is first generated. The model is chosen to apply to a range of plasma parameters descriptive of the synchronous satellite's tenuous particle and field environment.

Electrical properties such as conductivity and self inductance of discharge streamers is then estimated. The synthesis of discharge current wave forms can be undertaken as determined by the time dependent processes of charge separation, plasma breakdown, discharge streamer growth, and discharge current flow with equalization of charge separation.

In focusing investigation in this manner, a range of estimated current wave forms and their spectra corresponding to a range of satellite plasmas can be generated. These can be compared with experimental measurements and with satellite data as a basis to refine or alter plasma models and calculations.
APPENDIX A

PLASMA PARAMETERS
$\beta$ - ratio of plasma pressure to $\bar{B}$ pressure = \( \frac{8\pi n kT}{B^2_0} \)

\( n_0 (\text{cm}^{-3}) \) - particle density (specie $\sigma$, $\sigma = e$ + electron)

$T(o_k)$ - absolute temperature

$B(G)$ - $\bar{B}$ field in Gauss

$\lambda_D (m)$ - Debye length = \( \frac{\varepsilon_0 kT}{\sqrt{2e^2 (1 + Z^2)} n_e} \) (MKS units)

$\frac{4\pi n\lambda_D^3}{3}$ - number of particles in a Debye sphere

$\ell (cm)$ - characteristic scale of plasma region

$\lambda (cm)$ - mean free path = $C_{th}/\nu$

$\nu (s^{-1})$ - collision frequency of a particle

$u_\perp$ is velocity $\perp$ to $\bar{B}$

$r_{LE} (cm)$ - electron gyration radius = $m_e u_{LE}/eB$

$r_{LI} (cm)$ - ion gyration radius = $m_i u_{LI}/eB$

$\nu_E (s^{-1}) = e B/m_e c = \frac{U_{LE}}{r_{LE}} = $ Larmor frequency of electrons

$\nu_I (s^{-1}) = e B/m_i c = $ Larmor frequency of ions

$\lambda_L = $ mean distance of closest approach + PE. = $K.E.$

\( (i.e., \lambda_L = Ze^2/kT = 1.67 \times 10^{-3} Z \quad \text{g}^{-1}) \)

$\kappa n (A^{-1}) = \kappa n \frac{\lambda_D}{\lambda_L} A^{-1} = 4.9 \times 10^{14} \ell^2 n^{-\frac{3}{2}}$

**NOTE:** $\Lambda$ is an important parameter which indicates the degree to which collective effects exceed individual particle effects.
\[ C_{\text{th}} = \text{thermal velocity} = \sqrt{\frac{3kT}{m}} \quad m = \text{particle mass} \]

\[ \lambda_B = \frac{\hbar}{mC_{\text{th}}} \]

\text{NOTE:} \quad \lambda_B \ll \ell, \eta \implies \text{quantum effects are negligible} \]

\[ \omega_p (s^{-1}) = \text{plasma frequency} = \frac{C_{\text{th}}}{\lambda_D} = \left( \frac{4\pi n e^2}{M_e} \right)^{\frac{1}{2}} \quad = 5.6 \times 10^{-4} n_e \]

\[ \tau = \frac{1}{v} = \text{average time of one collision} \]

\[ \delta = \frac{\text{electrostatic energy}}{\text{thermal energy}} = \frac{e\Phi}{kT} \]

\[ \delta \text{ small implies plasma behaves thermodynamically as a perfect gas,} \]

\[ p = nkT \]

\[ \alpha = \text{degree of ionization} \]

\[ \alpha < 10^{-4}, \quad N_E \ll N \quad \text{weakly ionized} \]

\[ \alpha > 10^{-4}, \quad N_N \ll N_E \quad \text{strongly ionized} \]
APPENDIX B

PLASMA MODELS

FIGURE 2
Figure 2 Plasma Models