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CONTRACT TECHNICAL NOTE

THE RADAR ABSORPTION EFFECT CAUSED BY VERY THIN PLASMA SHEATHS

H.M. MUSAL, JR. AND W.E. BLORE

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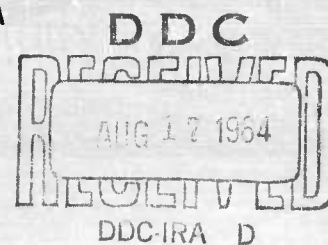
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SANTA BARBARA, CALIFORNIA

AEROSPACE OPERATIONS DEPARTMENT

CTN64-02

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VERY THIN PLASMA SHEATHS

ABSTRACT

The radar absorption effect has been observed in full scale

reentry vehicle tests and in laboratory and field studies of hypersonic

vehicle flow field observables. The usual manifestation of this effect

is the drastic reduction of the radar cross section of the vehicle and

its associated flow field under certain conditions. Ballistic range

studies of this effect have shown significantly large absorption to

occur for even very thin plasma sheaths. This is inexplicable in

terms of the theory that explains the full scale vehicle results. A

more advanced theory is presented here, which has the potential for

explaining the anomalous absorption caused by very thin plasma layers

covering blunt metallic bodies. In essence, it is shown that the ano-

malous absorption may be a diffraction effect caused by the gradient

of the electron density in the plasma sheath around the body. That is,

the effect occurs when the body is only partially covered by an over-

dense plasma sheath. This plasma layer can be very thin compared to the

wavelength of the radar wave and still cause a significant decrease in

the radar cross section. These results are illustrated by several theoretical graphs that show the dependence of the radar cross section of a metal sphere partially covered by a plasma layer on the size, thickness and properties of the layer. Finally, this theory is applied to predict the anomalous absorption observed in ballistic range studies. The large amount of absorption observed experimentally is correctly predicted by this theory, but an accurate verification of all the details of the behavior as a function of ambient air density and body speed awaits more extensive and detailed flow field computations.

THE RADAR ABSORPTION EFFECT CAUSED BY
VERY THIN PLASMA SHEATHS

INTRODUCTION

The radar absorption effect has been observed in full-scale reentry events, in small-scale field tests, and in laboratory studies. The usual manifestation of the radar absorption effect is the drastic reduction of the radar cross section of the vehicle and its surrounding flow field under certain flight conditions. The decrease in radar cross section is of the order of 10 to 20 db. This effect has been observed in two different flight regimes. It has been observed at high altitudes during reentry of the MIT Trailblazer Vehicle[1]. It has also been observed at relatively low altitudes during the reentry of full-scale reentry vehicles[2]. The laboratory observations of this phenomenon have been at relatively high ambient air densities and low velocities, which corresponds to the low-altitude observations in the full-scale situation. These observations have been made at GM DRL[3] and at CARDE[4].

Several attempts to explain the radar absorption effect have been made. In the case of the full-scale observations, these have been explained qualitatively and quantitatively by Musal[5]. This was done on the basis of a simple geometrical optics approach. Radar wave

destructive interference and real power absorption in the plasma sheath
surrounding the nose cone was shown theoretically to give rise to the
amount of absorption, and the altitude at which it occurred, actually
measured during the reentry. In this situation the thickness of the
plasma sheath was of the order of one-half the wavelength of the radar
wave. This is approximately the minimum thickness for which the
simple geometrical optics explanation will predict large amounts of
absorption. In the case of the MIT Trailblazer experiments, Murphy[1]
has offered an explanation for the high altitude radar absorption which
occurs at relatively high velocities. His explanation is based on the
fact that the plasma layer surrounding the vehicle may be much thicker
than the shock stand-off distance because of ultraviolet photoionization
of the air in front of the shock. This effectively creates a large cloud
of low density ionization around the vehicle. There is also gradual
radial gradient of the electron density in this cloud. At the radar
frequency used in this experiment, a strong interaction between the
wave and the ionization cloud was experienced. The net effect was to
decrease the backscattering from the entire structure. The ballistic
range experimental results obtained at GM DRL and at CARDE are not
explainable by either the simple geometrical optics approach or by means
of the photoionization assumption. The first explanation is not

applicable because the shock layer is too thin. Calculations have

shown that in order to predict the amount of absorption experimentally

observed, it would be necessary to assume that the shock layer was

three times as thick as was actually measured. The possibility that

photoionization would contribute toward a larger ionization cloud

around the body was disproved by measurements of the amount of

precursor ionization outside of the shock front. This was done in a

series of measurements at GM DRL[6].

In order to explain the absorption effect for the thin plasma sheaths

that are present in the ballistic range measurements several other

mechanisms were investigated. The possibility that the angular gra-

dient of the electron density around the body might cause focusing or

defocusing effects was investigated. Using a geometrical optics

approach, Musal[7] showed that the refractive effect of the gradient can

cause significant focusing and defocusing of the backscattered radar

wave. However, it was shown that in order to predict significantly large

amounts of absorption by this mechanism, the plasma layer again had

to be approximately two or three times as thick as was measured.

The angular gradient in electron density can be considered from

another viewpoint. This is the diffractive aspect of such a non-uniform

layer. The results of this approach will be outlined here since they

appear to contain the basic elements for the explanation of the radar

absorption effect caused by very thin plasma layers on metallic bodies.

THEORY

A theory that appears to offer a possible explanation for large decreases in the radar cross section of a metallic body when it is partially covered by a thin plasma layer is presented here. This theory depends on the diffractive effect of angular gradients in the plasma layer around the body, and predicts large decreases in radar cross section caused by very thin plasma layers.

The radar cross section of a body can be predicted theoretically in exact form if the tangential components of the electric and magnetic fields induced on the surface of the body by the incident radar wave are known exactly (see for example, Mentzer[8]). In the practical situation, the exact fields are usually not known. Thus some approximate method must be used to obtain approximate values of these fields when the body and the incident wave are specified. The well-known physical optics approximation is often used when the body is metallic. In essence, this approximation takes for the tangential induced fields on the surface of the body a magnetic and an electric field which are just equal and opposite, respectively, to the tangential components of the magnetic and electric fields of the incident wave. A suitable integration of these

fields over the illuminated surface of the body then gives the far field scattered wave intensity, from which the radar cross section is determined. In order to extend this theory to the case of plasma covered metallic bodies, it has been assumed that the effect of the plasma layer is merely to change the phase and amplitude of these induced fields. If the layer is very thin this appears to be a reasonably valid approximation. The far field scattered wave is then computed in the same manner as in the usual physical optics approach.

When this technique is applied to the case of a metal sphere covered by a thin plasma layer the resultant integral for the nose-on backscattering radar cross section (σ) can be shown to be

$$\frac{\sigma}{\lambda^2} = \frac{\pi^3 a^2}{4\lambda^2} \left| \int_{x=0}^{x=4a/\lambda} (\Gamma_{TM} - \Gamma_{TE})\left(1 - \frac{x\lambda}{4a}\right) e^{+j4\pi\frac{h}{\lambda}} e^{-j\pi x\left(1 + \frac{h}{a}\right)} dx \right|^2$$

where Γ_{TM} and Γ_{TE} are the TM and TE mode reflection coefficients for a metal-backed plasma layer, given by

$$\Gamma_{TM} = \frac{\Gamma_{pTM} + e^{z}}{1 + \Gamma_{pTM} e^{z}}$$

$$\Gamma_{TE} = \frac{\Gamma_{pTE} - e^{z}}{1 - \Gamma_{pTE}\, e^{z}}$$

where Γ_{pTM} and Γ_{pTE} are given by

$$\Gamma_{pTM} = \frac{\left(1 - \frac{\Omega_{p}^{2}}{1 - j\Omega_{c}}\right)\left(1 - \frac{\chi\lambda}{4a}\right) - \left[\left(1 - \frac{\chi\lambda}{4a}\right)^{2} - \frac{\Omega_{p}^{2}}{1 - j\Omega_{c}}\right]^{1/2}}{\left(1 - \frac{\Omega_{p}^{2}}{1 - j\Omega_{c}}\right)\left(1 - \frac{\chi\lambda}{4a}\right) + \left[\left(1 - \frac{\chi\lambda}{4a}\right)^{2} - \frac{\Omega_{p}^{2}}{1 - j\Omega_{c}}\right]^{1/2}}$$

$$\Gamma_{pTE} = \frac{\left(1 - \frac{\chi\lambda}{4a}\right) - \left[\left(1 - \frac{\chi\lambda}{4a}\right)^{2} - \frac{\Omega_{p}^{2}}{1 - j\Omega_{c}}\right]^{1/2}}{\left(1 - \frac{\chi\lambda}{4a}\right) + \left[\left(1 - \frac{\chi\lambda}{4a}\right)^{2} - \frac{\Omega_{p}^{2}}{1 - j\Omega_{c}}\right]^{1/2}}$$

and z is given by

$$z = -j\,\frac{4\pi h}{\lambda}\left[\left(1 - \frac{\chi\lambda}{4a}\right)^{2} - \frac{\Omega_{p}^{2}}{1 - j\Omega_{c}}\right]^{1/2}$$

and λ is the radar wavelength, a is the radius of the sphere, and h is the thickness of plasma layer. The plasma properties are given by the normalized plasma frequency Ω_{p} and the normalized electron collision frequency Ω_{c}, which are

$$\Omega_p = \frac{\omega_p}{\omega} = \frac{1}{\omega} \left(\frac{q^2 N}{\epsilon m} \right)^{1/2}$$

$$\Omega_c = \frac{\nu_c}{\omega}$$

where ω is the radar angular frequency $(2 \pi f)$, ν_c is the electron collision frequency, ω_p is the plasma frequency, q is the electric charge carried by an electron and m is its mass, N is the electron number density, and ϵ is the capacitivity of free-space. It can be shown that if the reflection coefficients of the layer are not functions of the angle of incidence, then the above integral can be explicitly evaluated in closed form. This is not the case for a plasma layer. Consequently, the integral must be evaluated by numerical integration.

Some typical results of this approach are shown in Figures 1 and 2. These figures show the radar cross section of a metal sphere as a function of the amount of the sphere covered by a uniform thin layer of plasma. Figure 1 shows the change in the radar cross section as the layer becomes thicker. It can be seen that a layer of only 1/10 of a wavelength in thickness is necessary to give appreciable changes in the radar cross section as the amount of angular coverage is changed. Figure 2 shows the change in the radar cross section as a layer of constant thickness changes in its electron density. A change in electron

density from critical density to 100 times critical density is en-
compassed.

In order to gain some confidence in the validity of this theory,
several experimental measurements have been made involving more
controllable configurations and materials. These experimental
measurements have shown that the theory is remarkable good, pro-
vided that one does not consider bodies which have a large extent of
surface nearly parallel to the direction of incidence of the radar wave.

APPLICATION

The diffraction theory will now be applied to the ballistic range
experimental situation. A preliminary attempt to predict theoretically
the amount of absorption obtained in the GM DRL ballistic range studies
of the radar absorption effect is presented here. In order to do this
properly, it is necessary to know the spatial variation of the electron
density and collision frequency throughout the entire shock layer around
the body. The computation of these quantities in the flow field is a very
lengthy aerodynamic calculation. The flow field calculation must be
repeated at each speed and/or pressure for which the radar cross section
is to be calculated. In order to avoid this much extensive work at the
present time, we have taken some representative approximate variations

of the flow field properties for use in the preliminary radar cross

section calculations. The thickness of the plasma layer was taken

to be the thickness of the overdense region of the plasma sheath

around the body. The electron density and collision frequency within

this overdense region were taken to be the values which existed in the

stagnation region for the speed and ambient pressure considered.

In order to obtain the dependence of the radar cross section on body

speed, the way in which this overdense region thickens and spreads

over the body as a function of speed was approximated by extrapo-

lation of limited flow field data[9]. This approach only approximates

the actual flow field configuration. Using this approach, the radar

cross section was calculated as a function of velocity for the ambient

pressure used in the ballistic range studies. The theoretical results

are shown in Figure 3, along with the experimental data. It can be

seen that a large decrease in the radar cross section, of the order

of 15 db, is obtained with the new theory. Previous theories gave

approximately 3 db of absorption under these conditions. The details

of the fluctuations of the radar cross section at high velocities are

probably not significant because the flow field was only approximated

and the assumptions that were made were not very good for such a

large fractional coverage of the body. As was pointed out earlier, the

theory itself does not appear to be very accurate in this regime either.

The real significance of this theoretical calculation is that a very large decrease in the radar cross section is obtained with only a very thin plasma layer. The details of how the radar cross section varies with speed depend critically on the development of the ionization around the body. Thus there is a need for very good flow field calculations before exact comparisons between the theoretical and experimental results can be made. Work is continuing along the lines of improving the diffraction theory used in the prediction of the radar cross sections of plasma covered metal bodies, and in the calculation of the flow fields around blunt bodies.

CONCLUSIONS

It appears that a theoretical explanation for the large decrease in the radar cross section of a metal body caused by a very thin plasma sheath has been found. The decrease depends on partial coverage of the body by the plasma layer. In other words, it is the angular gradients of the plasma properties around the body that cause severe diffraction of the radar wave. This appears to be the explanation for the anomalous absorption measured in ballistic range studies. This

effect and its theoretical interpretation, when more highly refined, may be useful as a flow field diagnostic technique.

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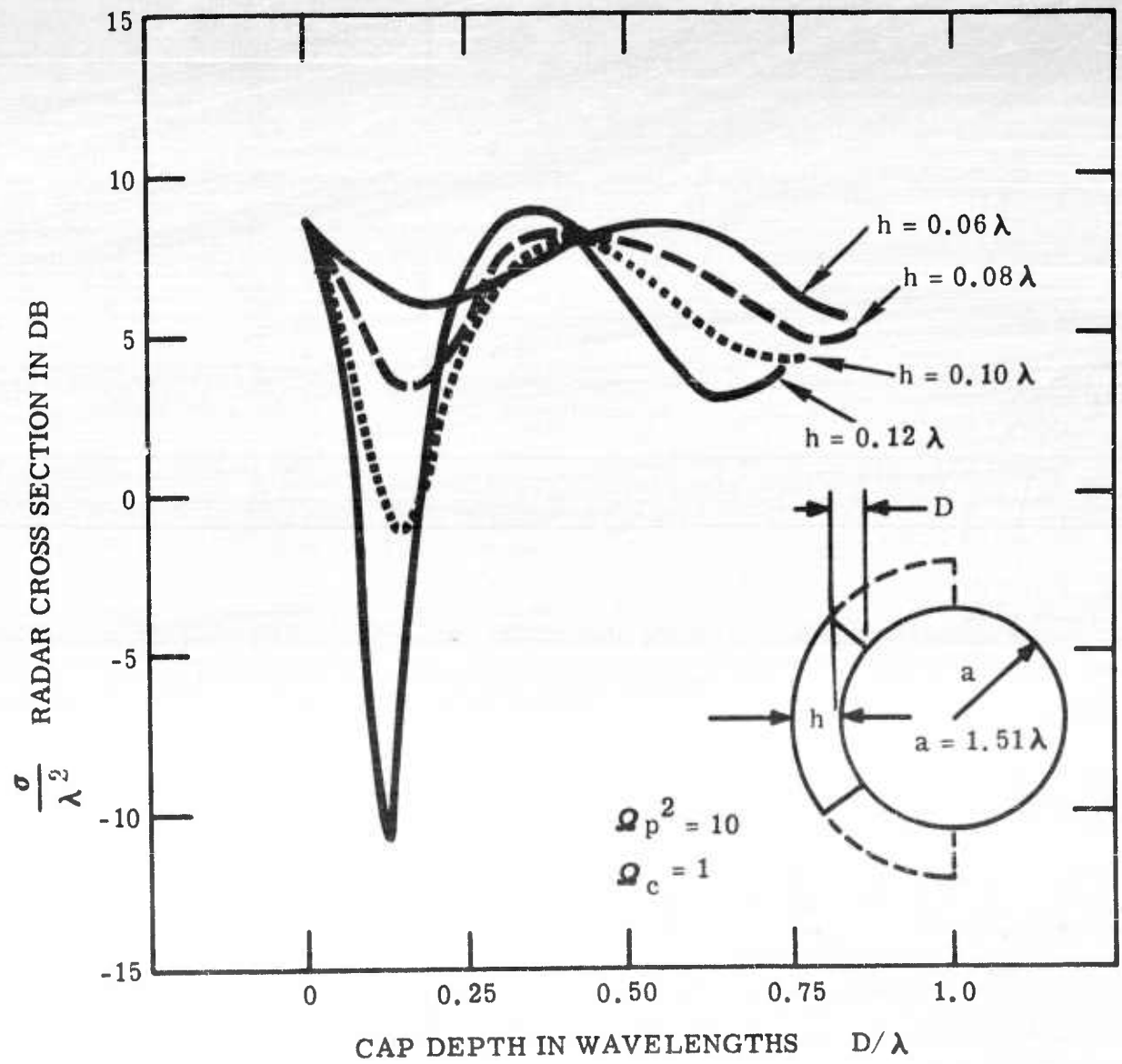
FIGURE 1   Radar Cross Section of Plasma
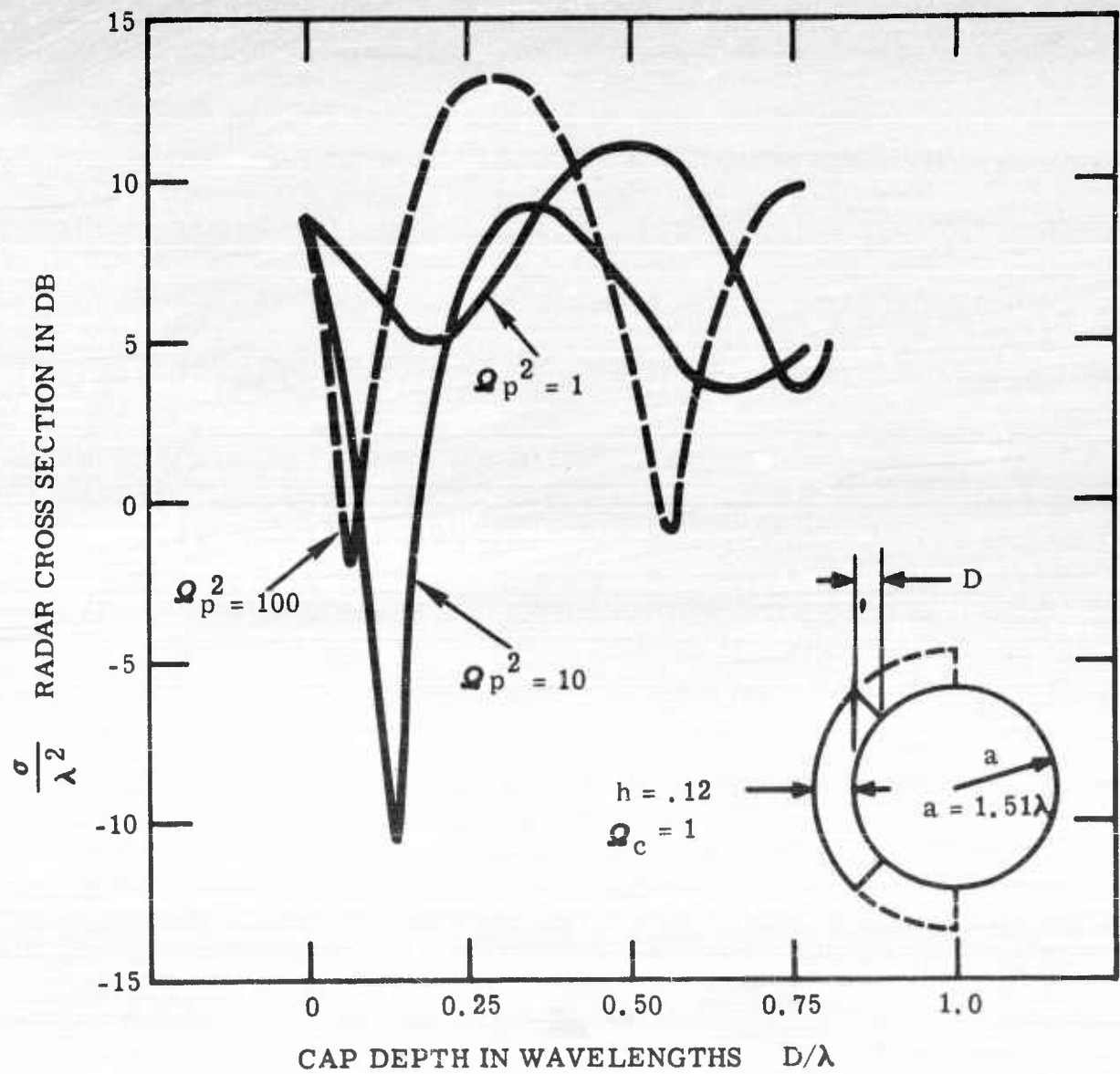Covered Metal Sphere-Effect
of Plasma Thickness

FIGURE 2   Radar Cross Section of Plasma
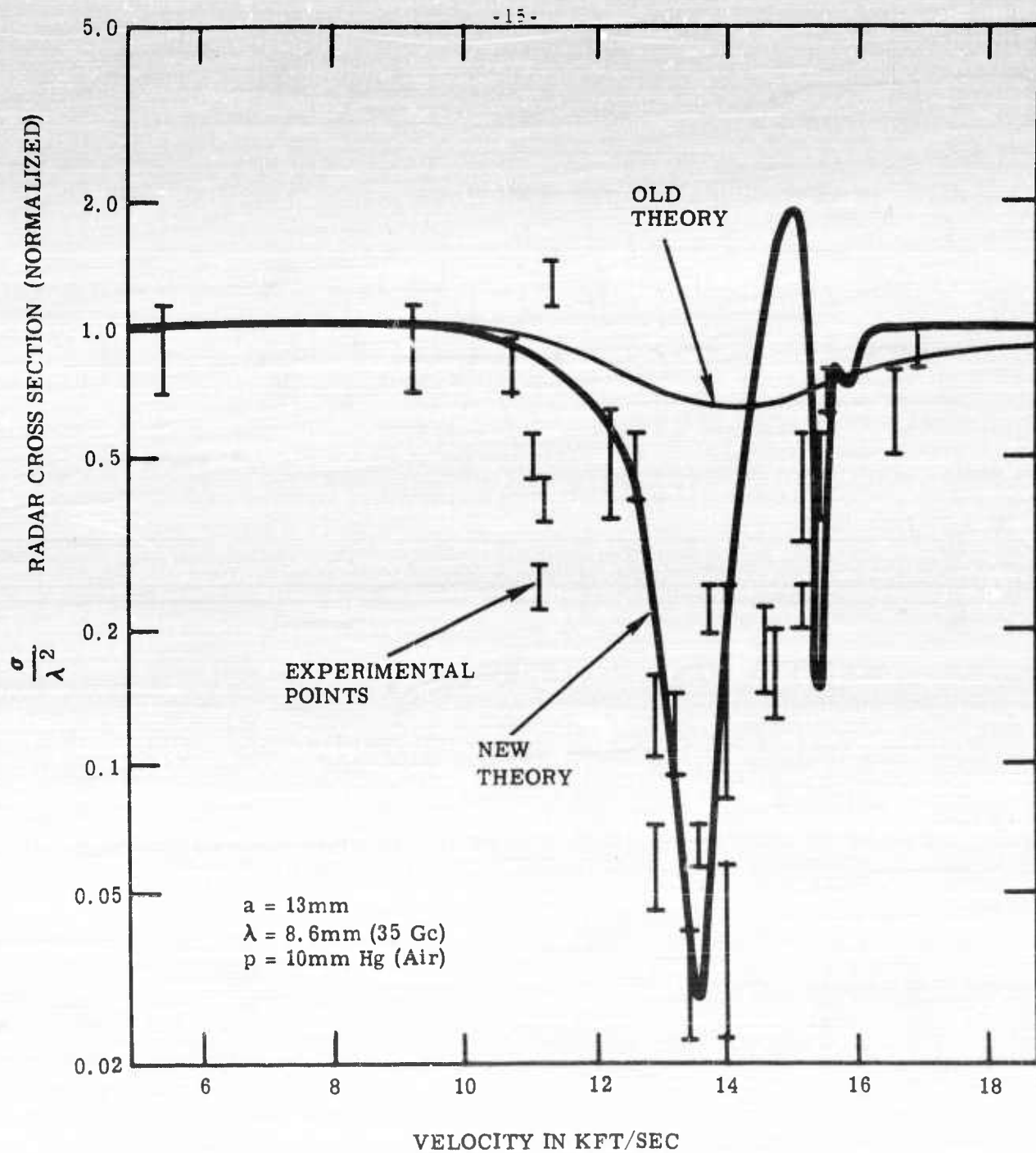Covered Metal Sphere-Effect
of Plasma Density

FIGURE 3   Radar Absorption Effect Observed
in Ballistic Range Compared
to Theory

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