Attitude-Control Rocket Exhaust Plume Effects on Spacecraft Functional Surfaces

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An analytical and experimental program was conducted to identify the contaminants that form during the pulse-mode operation of a liquid-bipropellant, attitude-control rocket engine to establish whether the trace metals found in the propellants exist in sufficient quantity to cause physical damage to spacecraft functional surfaces, and to attempt to show quantitatively the geometric boundaries of the continuum and free-molecular flow regimes found in the control-rocket exhaust plume. It was found that the principal contaminant produced was monomethylhydrazine nitrate. Analysis also indicated that the trace metals found in the propellants are capable of causing severe damage to spacecraft functional surfaces, particularly to Vycor optical windows. The phase of the study devoted to flowfield analysis indicated that the interface between the continuum and free-molecular flow regimes can be quantitatively identified through a determination of the rotational and translational freezing surfaces.

Introduction

IN recent years, the effect of an attitude-control rocket exhaust plume on a spacecraft and related functional surfaces has been the subject of considerable study. It is recognized that the control rocket produces contaminants that can significantly reduce the performance of optical windows, solar cells, and thermal-control coatings. This is particularly true when the rocket engine is operating in the pulse mode. The exhaust plume impingement pressure and heat-transfer phenomena also complicate the environment to which the spacecraft and its functional surfaces are exposed. In recognition of the serious nature of the problem, NASA and the Air Force have sponsored several industry-conducted analytical and experimental programs. In addition, both agencies have conducted comprehensive in-house studies on exhaust plume phenomena.

Based on the results of earlier Space Division studies and the work of other investigators,[1–7] a decision was made to focus the work described in this paper on such contaminants, their transportation from the thrust chamber to the spacecraft, and the mechanism by which damage is inflicted on spacecraft components. At least two different types of contaminants from engines have been observed: 1) a viscous, reddish-brown liquid that forms in droplets on the exhaust nozzle exit rim, and 2) "tramp" metals in the propellants that pass through the combustion chamber and are carried downstream by the exhaust plume at velocities of approximately 10,000 fps. The problem of flowfield analysis also is discussed.

Quantitative data are presented that permit identification of the continuum and free-molecular flow regimes, together with a method by which the characteristics-solution technique can be modified to produce meaningful solutions in the area of free-molecular flow.

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Analytical and Experimental Studies of Engine-Induced Contaminants

It has been known for some time that small, attitude-control rocket engines generate a viscous, reddish-brown liquid during pulse-mode operation. Although this material apparently does not affect engine performance, studies indicate that it degrades the performance of spacecraft functional surfaces and may be a contributory factor in the "pressure spike" phenomena associated with engine ignition in vacuum.

An extensive literature survey indicated that the steady-state combustion of N_2O_4 and amine fuels does not produce the detected contaminants. Pulse-mode operation, however, produces the materials presented in Table 1. In the case of the N_2O_4—monomethylhydrazine (MMH) rocket, the contaminant was identified as follows. Burch[1] had collected samples of it and published the spectrum shown in Fig. 1. During the present study, a sample of MMH nitrate was prepared in the laboratory by displacing ammonia from ammonium nitrate by MMH. An infrared spectrogram (Fig. 2) was prepared utilizing a salt (NaCl) substrate. Comparison of Fig. 2 with Fig. 1 and other figures offers conclusive evidence that MMH nitrate is the material produced in this case. The work of Refs. 2–7 produced a similar trend.

Salt-plate substrates were also used as a means of identifying the contaminants observed during the experimental phases of the program.[8] Although N_2O_4-MMH was one of the propellant combinations utilized, the infrared spectrographs obtained did not agree with those in Figs. 1 and 2. Figure 3 is representative of the spectrum obtained from a salt plate exposed to drops of liquid N_2O_4 and allowed to stand overnight.

Table 1 Nitrates identified in engine condensates[a]

Fuel	Nitrate
Hydrazine	Hydrazine nitrate
MMH	MMH nitrate
A-50	Hydrazine nitrate
UDMH	Ammonium nitrate

[a] N_2O_4 used as oxidizer in all cases.

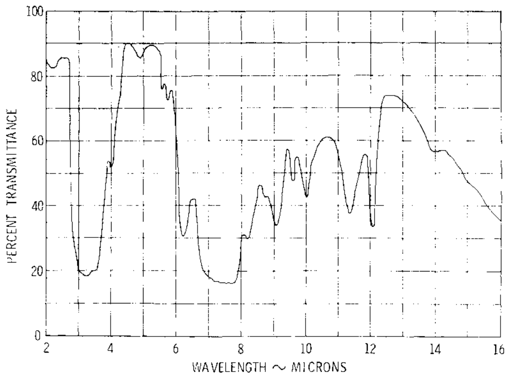


Fig. 1 Infrared transmission spectrum of residue from synthesis of MMH-NO_3.

During the post-test examination of one of the zinc-oxide thermal-protective coatings used during the Air Force program, a contaminant had been observed that was not identified because none of the material recorded in the Aerosystems Group's x-ray diffraction libraries showed the same "*d* spacings" as the deposited contaminants. It is believed now that the material probably was MMH nitrate. The absence of meaningful quantities of MMH nitrate is probably due to the pulse-width and engine-duty cycles utilized in the test program, where the shortest duration pulse width employed was 100 msec. Pulses of between 10 and 15 msec, fired with the engine cold, have been observed to produce substantial quantities of MMH nitrate.

Efforts to discover an additive or catalyst that would reduce or eliminate the contaminant were unsuccessful. The published work of other investigators[9–11] in this area yielded nothing that could be considered a possible solution.

Analytical Studies of the Damage-Producing Capabilities of Propellant Tramp Metals

The propellants used during the Air Force sponsored program, which were procured and used in compliance with applicable Government specifications, were found to contain a total tramp-metals concentration on the order of 120 parts per million. A Vycor optical window exposed to perpendicular plume impingement from a 22-lb-thrust engine turned opaque and lost more than 99% of its transmittance (Fig. 4). Figure 4 also indicates the condition of crown glass exposed to parallel and perpendicular impingement. Transmittance losses ranged from 6% to 99%. The damage to these surfaces and to other hardware appeared to have been caused by a sand-blasting or particle-bombardment phenomenon.

In addition to the tramp metals, other particle sources were considered as potential damage mechanisms, for example, ice and engine fabrication materials eroded during operation. Through utilization of a computer program that predicts the equilibrium chemical composition of the exhaust products, it was found that neither ice nor liquid water is formed under the test conditions to which the sample coupons were exposed. It was also found that erosion of metallic particles from the injector or thrust chamber could not occur in sufficient quantity to cause the observed damage. These two phenomena, therefore, were eliminated, and the main effort was concentrated on the tramp metals. The results of this study are presented in Fig. 5. With the knowledge that the Vycor was exposed on the order of 90 sec, the reader may see from Fig. 5 that the tramp metals in the propellants are capable of causing the damage observed. The ordinate of the figure indicates percent area per unit time impinged by particles. The rocket engine used in the test program had an expansion ratio (ϵ) of 40. The ϵ's indicated in the figure are "effective" values used to compute flowfield composition in the vicinity of the samples.

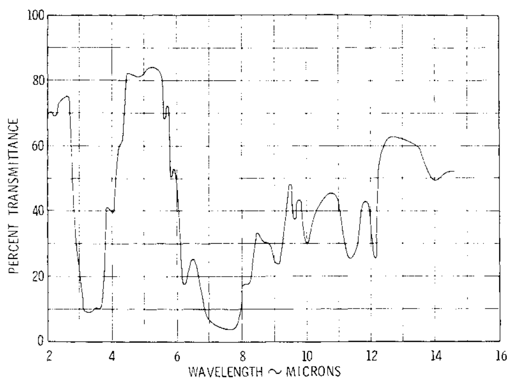


Fig. 2 Infrared absorption spectrum of pulse-generated contaminants.

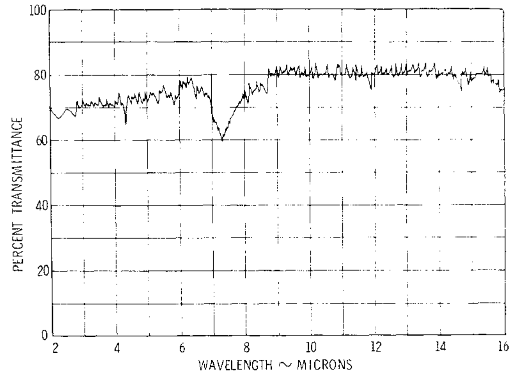


Fig. 3 Infrared transmission spectrum of deposits on NaCl salt-plate substrate.

Electron Microscopy

Many of the test articles exposed to the rocket exhaust plume had been examined with an optical microscope before and after testing.[8] During the present study, they were reexamined by electron microscopy, and the rear, unexposed faces of the glass samples were considered as representative of pretest surfaces. Electron microscope photographs (3000X) were produced and, in some cases, stereo pairs were prepared. Figure 6a presents a frosted Vycor glass stereo pair with the surface not cleaned before examination. Figure 6b shows the same glass in stereo with the surface cleaned. The latter picture was taken because there was a possibility that the cleaning process could change the condition of the

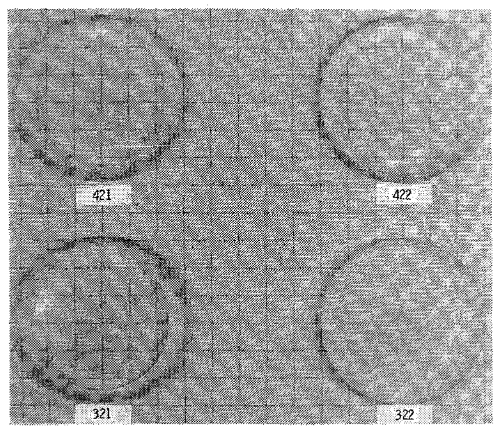


Fig. 4 Optical windows (post-test). 421—crown glass, parallel impingement; 422—Vycor, parallel impingement; 321—crown glass, perpendicular impingement; 322—Vycor, perpendicular impingement.

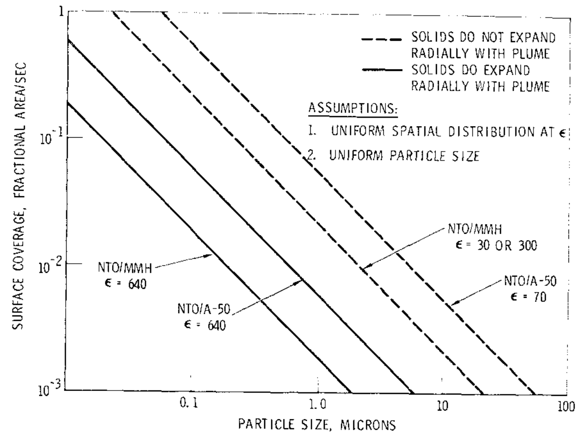
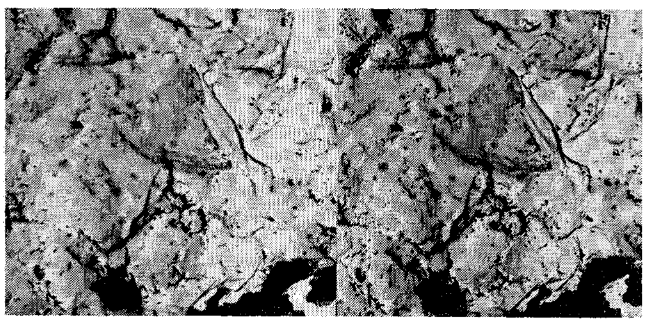


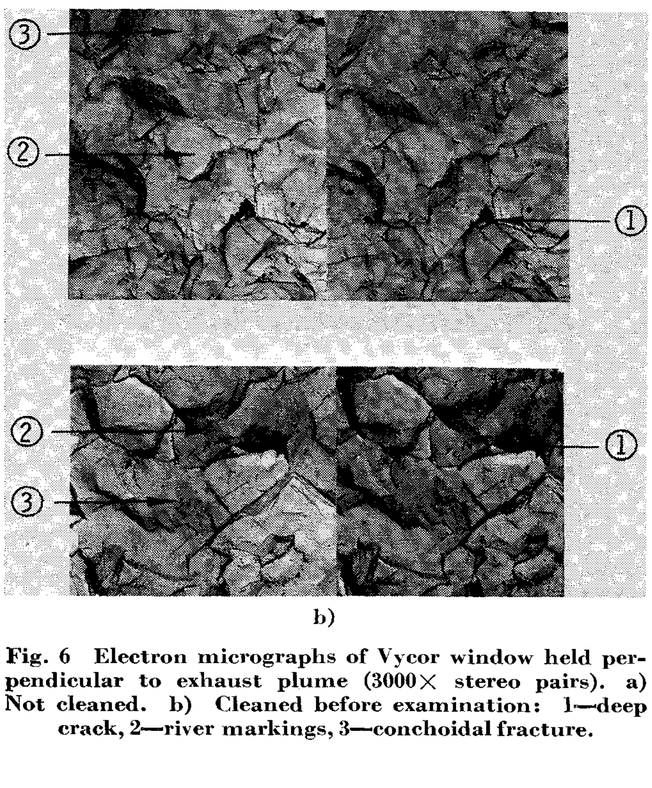
Fig. 5 Surface coverage rate of condensed tramp metals.

surface. Figures 7a and 7b present photographs of the crown glass window used in the perpendicular impingement test, uncleaned and clean conditions, respectively. (To obtain full benefit of the stereo pairs, one should use suitable viewer, such as a CF-8 stereoscope manufactured by the Abrams Instrument Corporation.)

Before the photographs of the damaged Vycor in the cleaned condition were taken, an unusual event occurred. For the purpose of identifying any residual materials remaining on the surface of the Vycor, the x-ray diffraction tests conducted during the Space Division/Air Force program were repeated



a)

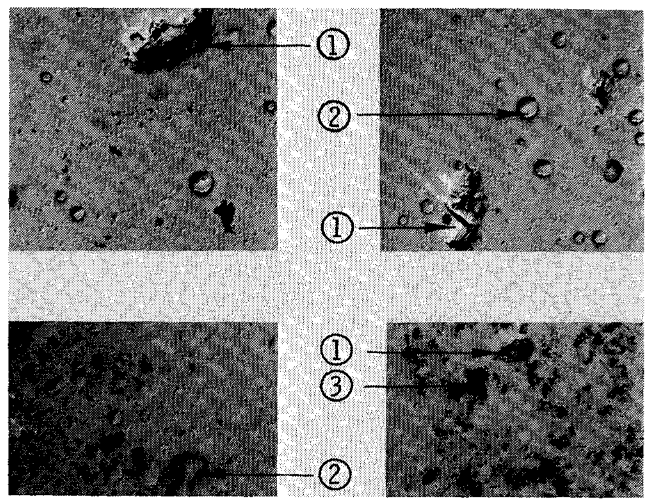


b)

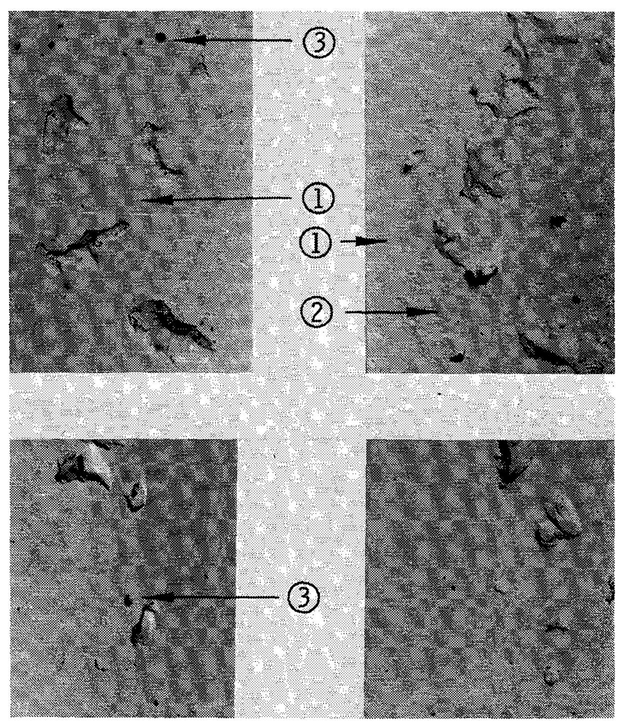
Fig. 6 Electron micrographs of Vycor window held perpendicular to exhaust plume (3000× stereo pairs). a) Not cleaned. b) Cleaned before examination: 1—deep crack, 2—river markings, 3—conchoidal fracture.

The exposure time, however, was increased from 45 min to 4 hr at an energy level of 40 kw at 20 Ma. The Vycor turned black (Fig. 8). In previous experiments, similarly darkened specimens had returned to their original condition after being slowly heated. This procedure was followed, and it was observed that at 600°C (Vycor melting point ~1600°C) the discoloration had disappeared, and the glass appeared to be in the condition indicated by Fig. 4 (322). The glass was then cleaned, and the photographs shown in Fig. 6b were taken.

To aid in interpretation of the stereo-pair photographs, a contour map (Fig. 9) and single-line traverse of the specimen were prepared. The latter indicated that the maximum peak-to-valley distance measured was 5 μ.



a)



b)

Fig. 7 Electron micrographs of crown glass window held perpendicular to exhaust plume (3000×). a) Not cleaned: 1-chip, 2—probable surface contamination (dirt), 3—as 2 but removed into replica. b) Cleaned before examination: 1—fibers adhering to surface after swabbing, 2—probable residual contamination, 3—contaminant removed into replica.

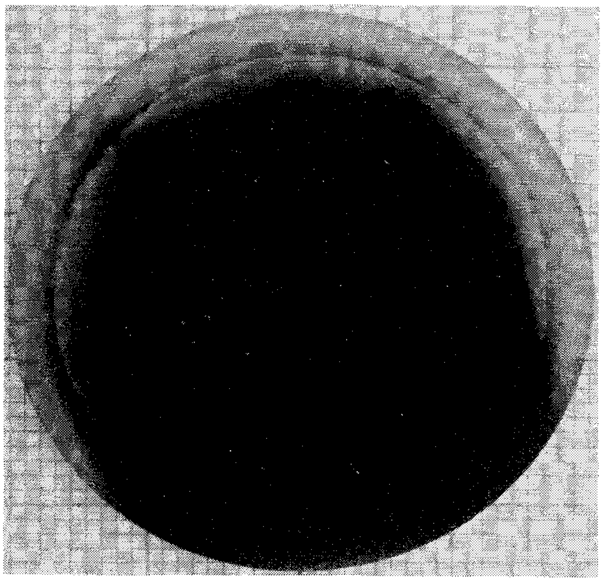


Fig. 8 Vycor optical glass after x-ray diffraction experiment.

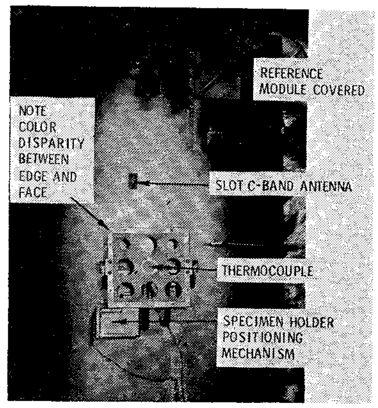


Fig. 10 Specimen holder positioned to accept simulated solar radiation.

The specimen holder also showed evidence of particle bombardment. Figure 10 shows the specimen holder rotated 90° to receive radiation from the solar simulator. Figure 11 presents the general arrangement used in the parallel impingement experiment. It can be seen that the center portion is considerably darker than the edges. Although difficult to detect in the picture, the darker portion is raised between $\frac{1}{8}$ and $\frac{3}{8}$ in. above the plane of the lighter-hued edges. Before initiation of the test, the entire surface of the holder was the same color and received the same protective coating. The uniform nature of the surface condition in the discolored area suggested that the change in color might be due to a thermal phenomenon rather than to particle bombardment. (Analysis had shown that the rocket exhaust gases could sweep over the raised portion of the holder and not come in contact with the edges.) Accordingly, samples of the specimen holder material (6061T6 aluminum) were obtained and were anodized by the same process used on the specimen holder. The samples were heated both in an oven and with a torch. Neither technique produced the effect shown in Fig. 10.

During the course of the study, it was observed that the discolored material could be readily removed by scraping. x-ray diffraction analysis performed on a sample scraping indicated that the material was aluminum. Figure 12 shows the 3000 × stereo pairs prepared from a representative section of the discolored area. As in the case of the Vycor glass, the photographs suggest that damage was due to particle bombardment.

Fig. 9 Contour map of frosted Vycor.

Flowfield Analysis

The prediction of exhaust-plume-induced impingement pressure and heat-transfer phenomena requires an accurate determination of plume geometry and related physical properties. For the earlier study,[8] extensive use was made of a computer program based on the method of characteristics. This technique is satisfactory for the continuum flow case but is not applicable to the free-molecular flow regime. Therefore, a technique was developed to identify quantitatively the boundary between the continuum and free-molecular flow regimes. The analysis was based upon the sudden freezing model proposed by Knuth[12] and is analogous to Bray's[13] criteron for freezing during chemical recombination. With this task accomplished, it was possible to modify the method of characteristics solution in such a way that useful data could be obtained for the free-molecular flow.

As the rocket engine exhaust gases expand, the density and temperature decrease, as does the number of interparticle collisions. Since the number of collisions required for equilib-

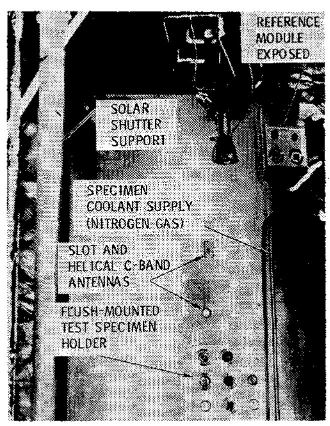


Fig. 11 Test panel installed in the simulated-altitude test facility.

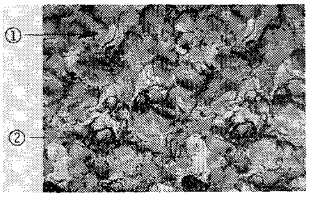


Fig. 12 Electron micrographs of sample holder—exposed surface not cleaned before examination (3000×) stereo pairs). 1) Artifact, 2) possible artifact at bottom of pit.

rium of the vibrational, rotational, and translational degrees of freedom are on the order of 100, 10, and 1, respectively, the vibrational degree of freedom freezes first and the translational degree of freedom freezes last as the gas expands. For the expansion of a gas from the exhaust nozzle exit into a vacuum, the vibrational and chemical degrees of freedom can be assumed to be frozen at the nozzle exit, and only the translational and rotational relaxation effects need be considered.

The results of the application of the method described above to a representative exhaust plume are presented in Fig. 13. For a complete analysis, the location of the translational freezing surface should be determined and included in the figure. The flow downstream of the translational freezing surface would be entirely in the free-molecular flow regime; the flow between the rotational and translational freezing surface is representative of a transition or a mixed-flow area. The technique, employing only the rotational freezing surface, has been used to reaffirm that the experiments[8] were conducted in the continuum regime.

During the course of the several exhaust plume technology programs it was observed that there was a strong possibility that each family of small, attitude-control rocket engines has a characteristic signature. It was theorized that the signature originates in the injector and that the pattern should be clearly recognizable in the exhaust plume. Personnel at the Jet Propulsion Laboratory noted and photographed this effect while operating a Surveyor engine under simulated lunar-landing conditions. It would be desirable, therefore, to modify existing computer programs (which produce homogeneous plume profiles and properties) in such a manner that, given an injector type, a striated plume could be produced. Although a brief analysis indicated that such modifications may be possible, the effort required was inconsistent with the scope of this study.

Conclusions

The following conclusions were derived from the study described herein:

1) The principal contaminant produced during the pulse-mode operation of a liquid-bipropellant, attitude-control engine is a fuel nitrate. In the case of the N_2O_4-MMH propellant combination, the contaminant is MMH nitrate.

2) Efforts to identify an additive or catalyst capable of eliminating or inhibiting the formation of the contaminant were not successful.

3) It has been determined, with reasonable certainty, that the sandblasting effect observed during an earlier study is due to a bombardment by tramp metals found in both the fuel and oxidizer supply. The type and quantity of the metals observed are admissible under current military specification requirements.

4) Analytical methods were devised that permit the delineation of the continuum and free-molecular flow regime, and the existing characteristic flow-analysis technique was modified for use in the free-molecular flow area.

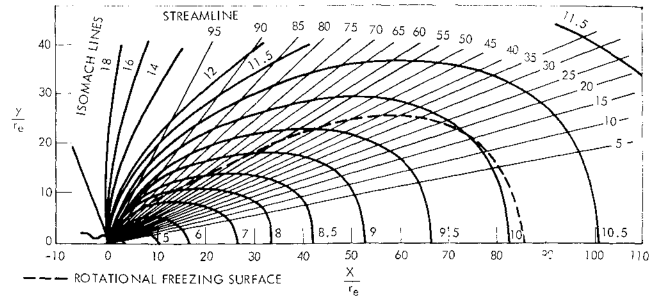


Fig. 13 Streamlines, isomach lines, and rotational freezing surface for exhaust plume flowfield (longitudinal and transverse coordinates referenced to nozzle exit radius).

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