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A Study of the Probability of Depositing Viable Organisms on Mars During the Mariner 1964 Mission

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CONTENTS

I. Introduction 1

II. Probability of Accidental Impact 2

III. Probability of Planet Contamination by Expelled Particles from *Mariner* Spacecraft 4

Reference 5

Appendix 6

FIGURES

1. Probability of planetary impact model 2

A-1. Orientation of spacecraft 6

A-2. Geometry where impact is possible 7

ABSTRACT

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A spacecraft aimed for the close vicinity of the planet Mars cruises through space leaving a trail of particles due to outgassing, firing of the hot motor used for midcourse maneuvers, and activation of the cold gas attitude control system. The ejected particles follow altered trajectories from their point of separation. It is shown that only the spacecraft itself and the attitude control system exhaust contribute significantly to the probability of planet contamination. The *Mariner* 1964 mission has been designed so that this probability is less than one part in ten thousand. This study considers the actual mission design and assesses the modifications which would be required if the desired probability were to be reduced to three parts in one hundred thousand.

Author

I. INTRODUCTION

To protect the planet Mars from possible contamination by viable organisms from the Earth, the National Aeronautics and Space Administration (NASA) has set the policy that any unsterilized spacecraft launched to Mars must have less than a 10^{-4} probability of accidental impact with the planet. In addition, in recent weeks the Committee on Space Research of the International Council of Scientific Unions (COSPAR) accepted, as tentatively recommended interim objectives, that the probability limit for accidental impact by an unsterilized fly-by or orbiting spacecraft be reduced to 3×10^{-5}.

This memorandum outlines in some detail the efforts and analyses which have been carried out by the Jet Propulsion Laboratory (JPL) to assure that the probability of accidental planet impact by the *Mariner* Mars 1964 spacecraft is less than 1×10^{-4}. In addition, the effect on this mission of adopting the more stringent 3×10^{-5} recommendations of COSPAR is assessed.

An estimate has also been made of the probability of viable organisms ejected from the spacecraft entering the Martian atmosphere even though the spacecraft does not impact the planet. These organisms are ejected from the spacecraft by the attitude control gas jets, the midcourse motor, and through the mechanism of outgassing by the spacecraft itself.

II. PROBABILITY OF ACCIDENTAL IMPACT

Before the probability of the spacecraft's accidentally impacting Mars is investigated a brief description of the mission profile is offered. The launch vehicle is aimed to send the spacecraft to the nominal aiming point. However, expected dispersions in the injection conditions will result in a high probability of the necessity for a trajectory correction maneuver. The maneuver will attempt to place the spacecraft on a trajectory passing through the nominal aiming point. If the initial maneuver fails to correct the trajectory and achieve an acceptable planetary encounter a second maneuver is available. It is obvious that following injection and one or both maneuvers, there is a finite possibility of having attained an impact trajectory by accident.

Figure 1 is a probability diagram of seven possible ways accidental impact may occur:

1. The spacecraft is on an impact trajectory at injection and cannot be maneuvered because of a malfunction.

2. The spacecraft is on an impact trajectory at injection. The first maneuver is unsuccessful and a second cannot be performed.

3. The spacecraft is on an impact trajectory at injection. The first maneuver is successful but a second maneuver, performed to improve the trajectory, results in impact.

4. The spacecraft is on an impact trajectory at injection. Each of the two maneuvers result in impact.

5. The spacecraft is not on an impact trajectory at injection. A maneuver required to improve the

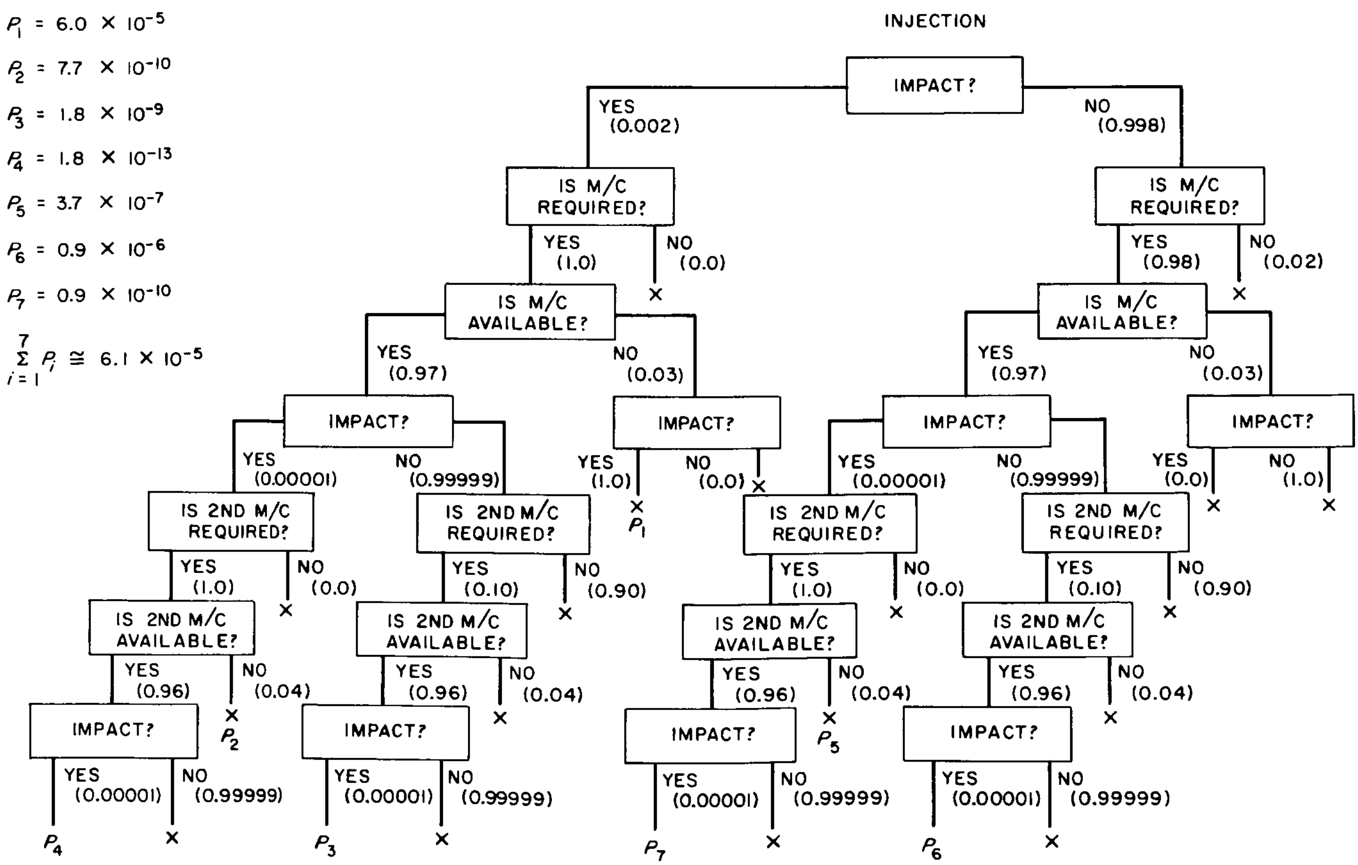

Fig. 1. Probability of planetary impact model

trajectory results in an impact trajectory and a second maneuver cannot be performed.

6. The spacecraft is not on an impact trajectory. The second of two maneuvers required to improve the trajectory results in impact.

7. The spacecraft is not on an impact trajectory. Each of the two required maneuvers results in impact.

The overall probability of impacting the planet is the sum of each of the above seven probabilities. In order to compute the individual probabilities the following assumptions are made.

1. The probability of the spacecraft impacting the planet at injection is 2×10^{-3}. This figure is found by mapping the injection dispersions given by the covariance matrix of injection errors, to the planet and integrating over the impact radius of the planet. Confidence in the accuracy of this quantity is very high.

2. The probability of requiring a midcourse maneuver even though the spacecraft is not on an impact trajectory is 0.98. This figure is found by mapping the injection dispersions, given by the covariance matrix of injection errors, to the planet and integrating over the area in which an acceptable encounter occurs. Once again, confidence in the accuracy of this quantity is very high.

3. The probability that the spacecraft will be able to execute a maneuver is assumed to be 0.97. This results from assuming the probability of the spacecraft being operable at injection is 0.98 and the probability of a successful motor burn is 0.99. The probability of being able to perform a second maneuver is assumed to be 0.96. Since the second maneuver will normally be performed within two weeks of the first maneuver, the probability of the spacecraft surviving this time span is assumed to be 0.99. Hence, $0.99 \times 0.98 \times 0.99 = 0.96$. The rationale and model used to compute these probabilities is included in detail in Ref. 1.

4. The probability of requiring a second maneuver is 0.90. This is computed by finding statistically the size of the first maneuver as a result of the injection dispersions. The dispersions in executing this maneuver, given by the covariance matrix of execution errors, are then mapped to the planet and integrated over the region of acceptable planetary encounter.

5. The probability of impact following a maneuver is 1×10^{-5}. This probability is computed by mapping the dispersions from the execution of the midcourse maneuver, given by the covariance matrix of execution errors, to the planet and integrating over the capture area of the planet. This quantity is highly sensitive to the size of the maneuver and the miss-distance. For the statistically expected size of the maneuver, the expected execution errors, and the nominal aiming point, the impact probability is at most 1×10^{-5}.

By utilizing these numbers in the model shown in Fig. 1, the seven individual probabilities can be estimated. Using the above estimates the total probability of planet impact is approximately 6.1×10^{-5}.

In judging the effect on the mission of reducing the impact probability to 3×10^{-5}, the COSPAR recommendation, it is evident that the overall probability of impact can be no smaller than the largest individual probability. The dominant term is the probability of impact at injection times the probability of being unable to perform a corrective maneuver. Using above estimates of probabilities this is 6×10^{-5}. The only method of reducing this probability is to reduce the probability of impact at injection by biasing the injection trajectories so that the probability of impact at injection is reduced to 1×10^{-3}. However, this implies changing the firing tables for the *Mariner* mission, an alternative clearly impossible at this late date in the mission. Additionally, biasing the trajectories implies a larger midcourse fuel requirement, which in general is an undesirable mission constraint. Hence, it is impossible for the *Mariner* Mars 1964 mission to satisfy the 3×10^{-5} probability of accidental impact criteria while easily satisfying the 1×10^{-4} required by NASA.

III. PROBABILITY OF PLANET CONTAMINATION BY EXPELLED PARTICLES FROM *MARINER* SPACECRAFT

In addition to the possibility of contaminating Mars by accidental impact the planet might also be contaminated by viable particles expelled from the spacecraft. These particles come from the gas expelled by the attitude control jets, the gases expelled by the midcourse motor, and the outgassing of the spacecraft.

It is estimated that the probability of viable organisms being expelled from the midcourse rocket motor is essentially negligible because of the extremely high temperature environment the particles must survive. Even if a viable organism survived, it would then have to travel at least 200 days through space to encounter Mars, since the maneuver occurs within the first few days of the mission. During this time, the particles would be exposed to continuous ultraviolet radiation with a high probability of destruction. In addition, as for any outgassed particles, the particle trajectory will be radically different than the spacecraft trajectory. Hence, the probability is negligible that particles from the midcourse motor would contaminate the planet.

Particles outgassed from the spacecraft have a negligible probability of contaminating the planet for two reasons. First, since the temperature of the spacecraft will be highest during the early phase of flight, it is expected that what little outgassing does occur, will take place during this time and hence the particles will be subjected to months of ultraviolet radiation. Also, the ratio of area to mass of the particles outgassed will be from 1,000 to 1,000,000 times that of the spacecraft and hence the effect on the trajectory of the particles due to solar pressure will be proportionally larger than on that of the spacecraft. The spacecraft nominally is blown about 20,000 km off course by solar pressure. Hence, even if the particles survive the ultraviolet environment they will undoubtedly be blown considerably off course by solar pressure.

The question of the probability of viable organisms in the attitude control gas impacting the planet is somewhat more complex since the gas jets *may* operate in the close vicinity of the planet. In this event, a small amount of the gas might impact the atmosphere of Mars if there were no further perturbations. However, four things should be pointed out:

1. The control gases leave the spacecraft with a relative velocity of 0.7 km/sec which implies they follow a considerably different flight path than the spacecraft.
2. The flight time to the planet will be measured in days or hundreds of days except for those particles expelled near the planet, and hence it is reasonable to expect the interplanetary environment to destroy any viable organisms except those emitted very near the planet.
3. With the solar sail control system functioning the number of attitude control jet actuations is expected to be reduced almost to zero, except during maneuvers; and hence, the amount of gas expelled should be very small.
4. The effect of solar pressure on the emitted particles will be a thousand to a million times greater than on the spacecraft. Particles emitted anywhere but very near the planet will be "blown" considerably away from the planet. Hence, it is considered highly unlikely that any viable organisms emitted prior to a few days from encounter will enter the Martian atmosphere.

A further study was made to estimate the probability that particles ejected near the planet will impact it. The mathematical model for these computations is shown in the Appendix in detail. It was assumed that the viable particles were expelled at constant velocity uniformly distributed in an exhaust cone about the jet nozzle axes. It was further assumed that only 1 out of every thousand organisms in the control system was expelled during this period because; (1) the control jets will, in all likelihood, not be operating due to the solar sails, and (2) some were already expelled during the flight. Assuming a 15,000-km miss-distance the number of particles, n, to enter the planet atmosphere was computed to be

$$n = 0.26 \times 10^{-8} N$$

where N = assumed number of viable organisms in the system.

The present filtering system in the attitude control system keeps the system extremely clean but not sterile. Hence, some viable organisms will exist. To estimate the number closely is nearly impossible, but rough estimates lie between 1,000 and 1,000,000. If there were on the order of 1,000 organisms then the probability of one of them impacting the planet is only about 10^{-5}. If, on the other hand, there were roughly 1,000,000 then the probability of one of them impacting the planet is about 10^{-3}.

In summary it can be stated with some assurance that outgassing and particle ejection from the midcourse motor have a negligible probability of impacting and contaminating Mars. However, the probability that viable organisms expelled from the attitude control system will encounter the planet is estimated to be between 10^{-3} and 10^{-5} depending upon the number of organisms present in the control system and the number of actuations of the gas jets.

REFERENCE

1. Billy, John M., *Probability of Success Model,* Jet Propulsion Laboratory, Pasadena, to be published.

APPENDIX

Since the attitude control gas is unsterilized, though filtered, some consideration must be given to the possibility of contaminating the planet Mars with viable organisms expelled through the gas jets. Some preliminary study shows that the simple model described below is fairly accurate and illustrates the dependence on the parameters of interest.

The model is based on the following assumptions:

1. N viable organisms at launch, expelled continuously during flight, such that a fraction, α of the total is expelled by encounter time, $0 < \alpha < 1$.

2. Organisms (not gas molecules) are expelled at constant velocity V_0, uniformly distributed in cone of half angle β about nozzle axis.

3. Capture cross section of Mars may be represented by a square that inscribes the actual circular capture cross section.

4. The trajectory may be approximated by a straight line (major contribution occurs near planet, but before encounter, when on asymptote of hyperbola). Hence, the time to go, τ, is used as the partial derivative of miss with respect to velocity, $\partial M/\partial V$.

5. Gas jets point in direction of roll axis (pitch and yaw jets) and in direction of yaw axis (roll jets). The spacecraft attitude is assumed constant with the actual near planet orientation.

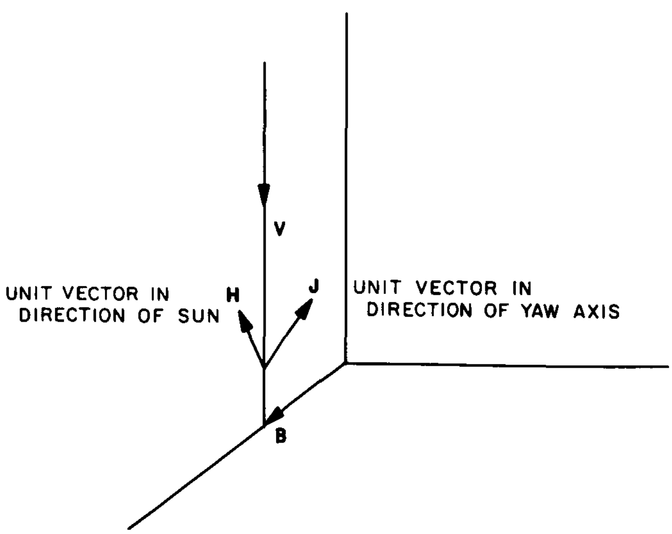

Fig. A-1. Orientation of spacecraft

Figure A-1 shows the orientation of planet and spacecraft, where **H** and **J** the unit vectors along negative roll axis (towards Sun) and yaw axis are shown relative to the velocity vector **V**, and miss-distance from the center of the planet **B**. Some thought shows that only the particles expelled from the jets pointing in the $-\mathbf{H}$ or $+\mathbf{J}$ directions can impact the planet. Figure A-2 shows the geometry at which impact can occur, where ψ is the angle between jet axis and velocity vector.

The number dn of particles that impact which are expelled in time dt is:

$$dn = \frac{\alpha N}{T}\left(\frac{2R_c}{2\beta V\tau}\right)^2 dt = -\frac{\alpha N}{T}\left(\frac{R_c}{\beta V}\right)^2 \frac{d\tau}{\tau^2} \qquad (1)$$

where T = time from launch to encounter. Therefore, as there are 12 jets, of which 4 point in the $-\mathbf{H}$ direction and 2 point in the $\mathbf{J}$ direction:

$$n = \frac{\alpha N}{6\tau_{0,H}}\left(\frac{R_c}{\beta V}\right)^2 \left(\frac{2}{\tau_{F,H}} - \frac{2}{\tau_{0,H}} + \frac{1}{\tau_{F,H}} - \frac{1}{\tau_{0,J}}\right)$$

where the times may be obtained from the geometry shown in Fig. A-2:

$$\frac{B}{R} = \frac{V}{V\tau_{F,H}} = \frac{V_0 \sin(\psi_H + \beta)}{V + V_0 \cos(\psi_H + \beta)}$$

$$\frac{B}{V\tau_{0,J}} = \frac{V_0 \sin(\psi_J + \beta)}{V + V_0 \cos(\psi_J + \beta)}$$

$$\frac{B}{V\tau_{F,J}} = \frac{V_0}{V}$$

$$\therefore n = \frac{\alpha N V_0}{6BV\tau_{0,H}}\left(\frac{R_c}{\beta}\right)^2 \left[\frac{2\sin(\psi_H + \beta)}{V + V_0\cos(\psi_H + \beta)} - \frac{2B}{VV_0\,\tau_{0,H}} + \frac{\sin(\psi_J + \beta)}{V + V_0\cos(\psi_J + \beta)} - \frac{1}{V}\right] \qquad (2)$$

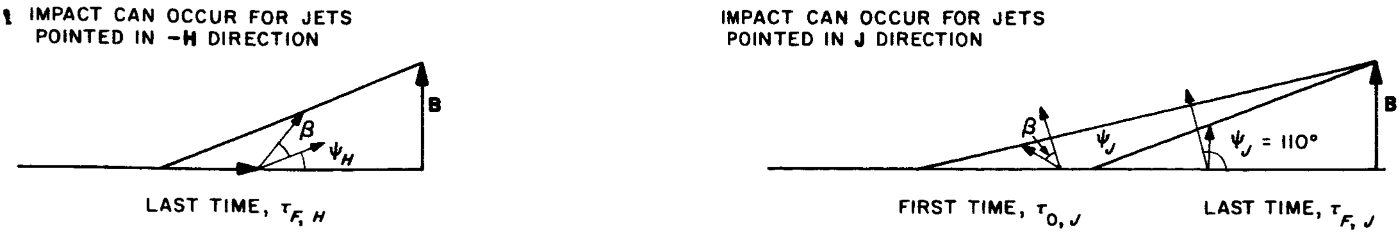

Fig. A-2. Geometry where impact is possible

With the following typical values:

$$\tau_{0,H} = 20 \times 10^6 \text{ sec}$$

$$V_0 = 0.7 \text{ km/sec}$$

$$V = 5 \text{ km/sec}$$

$$R_c = 5{,}300 \text{ km}$$

$$\psi_H = 20°$$

$$\psi_J = 110°$$

$$\beta = 30°$$

Equation (2) becomes

$$n = 0.039 \frac{N\alpha}{B}$$

Assuming that α provides for the fact that if the solar vanes work properly very little gas will be needed and only a small portion of the viable organisms will survive in the space environment (namely those in large clusters shielding the inner organisms from the ultraviolet radiation), then $\alpha = 0.001$ would be reasonable. A typical value of B would be 15,000 km so that

$$n = 0.26 \times 10^{-8} N$$