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STUDY OF PROPELLANT VALVE LEAKAGE IN A VACUUM

Final Summary Report

by Ralph D. Gift, John A. Simmons, Jack M. Spurlock, Joseph P. Copeland, and Jaydee M. Miller

Prepared by
ATLANTIC RESEARCH CORPORATION
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1.0 INTRODUCTION

This document is a condensed summary report of an investigation of the adverse effects of propellant leakage through propellant valves and into rocket injector manifolds and combustion chambers exposed to a vacuum environment. In space, during a non-firing condition, these various regions of the engine are exposed to a vacuum environment. Consequently, should any propellant leak past the control valve, it can freeze and accumulate in the injector flow passages and combustion chamber. The program of investigation described in summary form in this report was conducted to study the likelihood that such accumulation may cause blockage of the propellant flow system or result in a catastrophic "hard" start. The investigation consisted of concurrent theoretical and experimental studies, with emphasis of consideration being given to the factors that could affect the performance of the Apollo SPS (Service Propulsion System) and the Gemini OAMS (Orbit Attitude Maneuvering System) engines.

2.0 STUDY OBJECTIVES

The primary objectives of this work were to: (1) determine the extent of blockage of propellant flow systems caused by evaporatively frozen propellant when the propellant becomes exposed to a vacuum environment; (2) investigate the effects of such freezing on hypergolic ignition; and (3) conduct a preliminary study of the effectiveness of various remedial techniques.

3.0 RELATIONSHIP TO OTHER NASA EFFORTS

In a previous investigation for the George C. Marshall Space Flight Center[1,2], it was shown that most liquid propellants, particularly

[1]The detailed Final Report on this contract is NASA CR 62046.

[2]Atlantic Research Corporation, "Investigation of the Effects of Vacuum on Liquid Hydrogen and Other Cryogens Used on Launch Vehicles," Final Summary Report by J.A. Simmons, R.D. Gift, and M. Markels, Jr. for Contract NAS 8-11044, December 18, 1964.

nitrogen tetroxide and Aerozine-50 (the 1:1 mixture of hydrazine and unsymmetrical dimethylhydrazine), may freeze very rapidly when exposed to a vacuum environment. This results from the evaporation and its attendant cooling, which occurs from all exposed surfaces of the liquid. The exposed propellant will freeze if the magnitude of the rate of evaporative heat transport at the freezing temperature of the propellant is greater than the rate of heat absorption from the surroundings (solar radiation, heat conduction from rocket hardware, etc.). According to the theory of evaporation, described in Reference 1, the rate of evaporative heat transport is directly proportional to the vapor pressure of the material, but decreases with increasing ambient pressures. Significant ambient pressures may be created by enclosures which surround the evaporating propellant and impede the escape of vapor. Accordingly, the likelihood that a given propellant may freeze and accumulate within the injector flow passages and combustion chamber depends on the geometry of these enclosures and their thermal environment.

Several cases of evaporative freezing of propellant have occurred during static-test-firings of the Apollo Service Module engine (SPS) in a low-pressure environment. Although the freezing caused no apparent operational difficulties, an investigation seemed advisable to define the situation more fully.

4.0 METHOD OF APPROACH

The investigation was begun June 7, 1965 and consisted of four phases. Phase I was a study of the adverse effects resulting from leakage of nitrogen tetroxide (only) through a propellant valve into the flow passages of a manifold and injector system. A ball valve was used for the propellant valve, and a glass pipe (which permitted observation of the freezing phenomena) was used for the manifold. In general, the system that was used approximately simulated the Apollo SPS propellant flow system in a reduced scale. Phase II was a similar study with Aerozine-50 alone. Phase III was a study of adverse effects on hypergolic ignition, which are caused by the freezing of leaked propellant. For this study a 25-pound thrust engine with a glass combustion chamber was designed and used. Phase IV was a study of evaporative freezing of propellant within the injector flow passages of the Gemini RCS (Reentry Control System) rockets. This phase was added to the original investigation on December 10, 1965. The intermittent failure of several OAMS (Orbit Attitude Maneuvering System) rockets (very nearly identical to the RCS rockets) on the Gemini-5 vehicle possibly can be attributed to evaporative freezing of propellant within the injector and the consequent stoppage of propellant flow.

Each of the four phases of the investigation consisted of analytical and experimental efforts. In the former, a literature survey and analysis was made to elucidate the freezing characteristics of the propellants nitrogen tetroxide, Aerozine-50 (1:1 mixture of hydrazine and unsymmetrical dimethylhydrazine) and monomethyl hydrazine. Quantitative mathematical relationships between the rate of leakage and the accumulation of frozen propellant within the flow passages of an injector manifold were developed. For the experimental studies, tests were performed to (1) characterize evaporative freezing of the above-listed propellants and the dependency of such freezing on selected parameters; (2) to determine the extent of any flow stoppages caused by the accumulation of frozen propellant; and (3) to observe effects of leakage on hypergolic ignition.

5.0 BASIC DATA GENERATED AND SIGNIFICANT RESULTS

The principal result of this investigation was the experimental and theoretical demonstration that leaking propellants can freeze evaporatively in the injector manifold of a rocket engine, when exposed to a vacuum environment, and thereby can obstruct subsequent flow. Furthermore, the obstructions grow and break up in a cyclical manner, with the result that the seriousness of the blockage depends on the moment in this cycle at which the propellant valve is opened. Such blockage could prevent hypergolic ignition entirely, or cause a "hard start" and the occurrence of explosive pressure transients within the combustion chamber or injector manifolds.

In the experiments with nitrogen tetroxide and Aerozine-50, in an injector system simulating that used in the Apollo main propulsion systems, the longest delays were 8 and 75.5 minutes, respectively.

The significant processes of freezing and accumulation of frozen propellant, associated with propellant leakage into injector manifolds, can be explained by the general theory of evaporation and evaporative freezing. That the course of accumulation of frozen propellant, and the extent of the blockage created, is cyclical results from the fact that the accumulation is constantly being dissipated by sublimation and melting. When weakened by these dissipative effects, the plug of frozen propellant is broken away by the pressure of the liquid backed up behind it. The newly exposed liquid then begins to freeze evaporatively and a new plug is created. This repeats in a cyclical fashion as long as the leakage continues. If the leak rate is very low, the blockage occurs only in the vicinity of the leak. At higher leak rates, the site of blockage progresses, with each successive cycle, from the source of the leak through the flow passages to the injector, where it remains. The frequency of the cycles is approximately proportional to the leak rate since this determines the time required for liquid to fill the cavity behind the plug. To some extent the frequency also depends on the site of the plug; the ability of the frozen material to resist the propellant pressure depends on the mechanical support provided by the site. Thus, strong plugs are formed at bends, and points of abrupt reduction in flow area, such as at the injector ports.

The investigation also showed that leak-rate and injector orifice area had far more effect on the freezing mode than any of the other variables investigated. One of the most important characteristics of leakage of propellant into injector flow passages is that frozen propellant can accumulate in the passages only if the leak rate is within a certain range. The maximum of the range results from the fact that the vapor can escape only through the injector ports. Consequently the maximum rate of heat removal is limited by the total area of the ports. Therefore, if the propellant is a pure liquid, such as nitrogen tetroxide, the maximum of the leak range is defined by the condition that the rate of evaporative heat flow be just sufficient to cool and freeze the leaking propellant and simultaneously remove the heat transported to the frozen propellant from the surroundings. The minimum of this range is defined by the condition that the rate of heat transport from the surroundings be just sufficient to vaporize the propellant as fast as it leaks. In other words, there is no accumulation of frozen propellant within the manifold at leak rates less than the minimum or greater than the maximum value. However, at leak rates greater than the maximum, the propellant flows on into the combustion chamber where it may freeze and accumulate.

Based on the experimental and theoretical results, minimum and maximum leak rates for selected initial propellant temperatures were computed for the oxidizer and fuel injector systems of the Apollo SPS (Service Propulsion System) engine and the 25-and 100-pound-thrust OAMS (Orbit Attitude Maneuvering System) engines of the Gemini vehicle. The results are listed in Table 1. The minimum leak-rate values are order-of-magnitude estimates and reflect the attempt to select the lowest reasonable rate of heat transfer from the surroundings, considering all the various types of thermal environments in which the engines would be used. Accordingly, under most operational circumstances, the actual minimum leak rates may be somewhat greater than the values listed in Table 1.

These results predict that leakage, over a wide range of rates, of either nitrogen tetroxide or Aerozine-50 into the flow passages of the injector of the SPS engine can lead to an accumulation of frozen propellant. The same result is predicted for nitrogen tetroxide in the Gemini OAMS engines. On the other hand, monomethyl hydrazine, the fuel for the OAMS engines, cannot freeze in the flow passages since the evaporative heat flow at its triple point is less than the rate of heat transfer from the surroundings.

TABLE 1

COMPUTED MAXIMUM AND MINIMUM LEAK RATES FOR THE INJECTOR SYSTEMS OF THE APOLLO SPS AND THE GEMINI OAMS ENGINES

Engine	Propellant	Injector Port Area (in^2)	Initial Propellant Temperature (^oF)	Computed Leak Rate, cc/sec Maximum	Computed Leak Rate, cc/sec Minimum
Apollo SPS	Nitrogen Tetroxide	1.42	40	126.5	0.05
			130	89.1	--
	Aerozine-50	0.944	40	3.06	0.004
			80	11.40	--
			135	6.98	0.004
Gemini 25-pound OAMS	Nitrogen Tetroxide	0.00158	40	0.13	0.003
			80	0.11	0.004
	Monomethyl Hydrazine	0.00222	40	Does not freeze in the injector	
Gemini 100-pound OAMS	Nitrogen Tetroxide	0.00725	40	0.62	0.004
			80	0.54	0.004
	Monomethyl Hydrazine	0.0105	40	Does not freeze in the injector	

The limited number of hypergolic ignition sets of tests conducted did not allow resolution of all the questions. Nevertheless, in one experiment it was demonstrated that catastrophic overpressures could occur in the oxidizer manifold as a result of ignition following a fuel leak. On the other hand, no dangerous and excessive pressures were recorded in the combustion chamber as the result of ignition following either an oxidizer or fuel leak.

The apparently obvious method of preventing the freezing of leaking propellant is to heat the injectors. However, this approach is impractical for spacecraft because of the very large power inputs that are required to provide adequate heating. The power needed to prevent freezing, regardless of the leak rate, is prescribed by the fact that the range of leak rates for freezing must be zero, or in other words, the maximum and minimum leak rates must be equal. As an example, consider nitrogen tetroxide in the Apollo SPS engine. For an initial propellant temperature of $40^{\circ}F$, the power required is 20.2 kw!

Other remedial methods are suggested by consideration of the several factors governing the maximum leak rate. For example, the maximum leak rate is directly proportional to the triple-point pressure of the propellant, and accordingly the use of propellants with sufficiently low triple-point pressures would alleviate the problem. As demonstrated in the Gemini tests, monomethyl hydrazine, whose triple-point pressure is approximately 0.1 torr, cannot freeze evaporatively in the fuel flow-passages of the Gemini OAMS engines. However, monomethyl hydrazine is adequate for this purpose only for small engines, since it was also predicted that it can freeze in the injectors of large engines because of the differences in geometries (e.g., total injector-port areas, etc.) involved.

Another excellent approach to the problem is to minimize the likelihood of leakage. One means of effecting this is to use double (redundant) valving, a practice that has been adopted for all the main propulsion systems of the Apollo vehicles. However, because of the weight entailed, and the increased allowable response time required, the method probably is not practical for small control rockets.

6.0 LIMITATIONS

The experiments conducted in Phases I and II used an injector and propellant flow system which only approximately simulated the actual components of the SPS engine. Accordingly, the leakage conditions, which would adversely affect operation of the SPS engine, could not be obtained directly from the experiments. Instead, the adverse leakage conditions were calculated using the theory developed. The transparent flow system used in the experiments allowed visual observation of the freezing phenomena and provided the basic data which verified the theory.

A complete evaluation of the effects of propellant leakage in a vacuum environment, on hypergolic ignition could not be made because of the limited scope of the program. Although several important aspects were demonstrated by the hypergolic ignition tests (see Section 5.0), a more comprehensive study is necessary to define the effects on hypergolic ignition of such parameters as propellant temperature, injector and combustion chamber geometry, and leak rate.

Another limitation experienced during this program was the unavailability of appropriate thermodynamic properties of the 1:1 mixture of hydrazine and unsymmetrical dimethylhydrazine. Additional details on this subject are presented in Section 7.0

7.0 IMPLICATIONS FOR RESEARCH, AND SUGGESTED ADDITIONAL EFFORT

This investigation resulted in a good basic understanding of the types of problems encountered when propellant valves leak while exposed to the vacuum environment of space. Additional effort, however, is required to provide more detailed knowledge of the evaporative freezing phenomena under certain specific conditions. For example:

(1) A full-size SPS flow system should be tested in an adequate vacuum chamber. Althouth the sub-scale transparent flow system used in this study to simulate the SPS system was

necessary to obtain visual evidence of the various freezing modes encountered, its usefulness is limited. One of the major criteria which influence blockage of a flow system by evaporatively frozen propellant is the geometry of the system. Since the transparent, simulated SPS flow system only approximately represented the geometry of the actual system, additional effort should be directed toward testing a full-size SPS flow system under similar conditions, and using similar test procedures.

(2) Further investigation should be conducted to determine the thermodynamic properties of the hydrazine and unsymmetrical dimethylhydrazine mixtures (Aerozine-50). This will permit better, more reliable prediction of its freezing characteristics under various temperature and pressure conditions. A multicomponent system, such as this propellant mixture, exhibits complex thermodynamic behavior. For example, under significant changes of temperature or pressure the attendant phase changes (vaporization, condensation or freezing, etc.) produce changes in the composition of the various co-existent phases. Although a moderate amount of thermodynamic-property work has been accomplished and reported by various investigators for the pure constituents of the mixture N_2H_4 and UDMH, very little effort has been spent specifically in determining the important thermodynamic properties of the mixture. The recommended investigation should be conducted to determine those thermodynamic properties of the mixture which would be of major importance to research, development and design of space propulsion systems. A preliminary review of the literature indicated a need for a significant amount of additional P-V-T and vapor-liquid equilibria data, as well as calorimetric data on heats of solution and/or heats of vaporization.

(3) A detailed study should be conducted to define the effects of propellant leakage on hypergolic ignition of a rocket engine exposed to a vacuum environment. The brief hypergolic ignition studies conducted during this program demonstrated that series problems could be encountered (see Section 5.0) and that remedial measures should be developed to cope with the potential hazards involved.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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