

SESSION I

MECHANISM PROBLEMS

By John K. Riedel*

ABSTRACT

Too frequently during the design and development of mechanisms, problems occur that could have been avoided if the right question had been asked before, rather than after, the fact. Several typical problems, drawn from actual experience, are discussed and analyzed. The lessons learned are used to generate various suggestions for minimizing mistakes in mechanism design. These suggestions are intended to precipitate the right question at the right time; that is, before, rather than after, a test or flight failure.

INTRODUCTION

From a viewpoint of direct involvement in the design and development of various aerospace mechanisms in the past few years, it is disconcerting to realize how often failures or malfunctions occur. When viewed with hindsight, these problems cause one to wonder, "how could we have overlooked that?" This question is not concerned so much with anomalies revealed during early development testing; these anomalies are to be expected and are even needed during the design evolution. Rather, it is the failures that occur downstream during qualification or flight testing that are of greatest concern. These are the failures that cause embarrassment and consternation and which will be the subject of this report. Several examples will be cited, not only to illustrate typical errors but, more important, the lessons learned, followed by suggestions intended to improve future performance regarding mechanisms design. In presenting these examples, the role of design (as opposed to test and analysis) will be emphasized because this is where the responsibility usually rests and the blame falls.

TYPICAL PROBLEMS

Diaphragm Problem

Two problems that were encountered in the development of the radar augmentation device (RAD) (ref. 1) will be used as examples. In essence, the RAD is a self-inflating

*Lockheed Missiles and Space Company, Inc., Sunnyvale, Calif.

sphere that is used as a large reflector to facilitate early acquisition by the ground-based radars. It is inflated with Freon that is released from a reservoir when a spring-loaded piercer punctures a metal diaphragm at the outlet of the reservoir. It was recognized that temperature would affect the vapor pressure of the Freon and, thus, the rate of inflation of the sphere. Experience had indicated that, if the rate of inflation was too fast, the sphere or balloon, would burst. Therefore, one test was conducted at elevated temperature to verify sphere-inflation performance at the upper temperature limit. Instead of getting rapid inflation, just the opposite was obtained. By investigation, it was subsequently established that the increased vapor pressure was sufficient to overcome the force of the spring used to drive the piercer. As soon as the piercer punctured the diaphragm the increased vapor pressure acted on it to force it back before full penetration of the diaphragm was achieved. This problem is illustrated in figure 1. Subsequent redesign, shown in figure 2, incorporated a hollow piercer; thus, the vapor pressure could not act on it to force it back.

Orientation-Sensitivity Problem

On another occasion in the RAD program, a design flaw was discovered by "coming through the back door." In a test designed to evaluate improvement in packaging the sphere, the unit was mounted horizontally to eliminate the influence of gravity on sphere deployment. Deployment was satisfactory but, unaccountably, the rate of inflation was significantly slower than in all previous tests wherein the unit had been inclined downward. Subsequent investigation established that the design was sensitive to orientation. When the sphere was in the downward orientation, Freon entered the sphere as a liquid, whereas when the sphere was in the horizontal position, Freon entered the sphere as a vapor or gas. Thus, a much slower rate of inflation occurred when the sphere was in the downward orientation. This problem and its solution are illustrated in figure 3.

Moisture-Absorption Problem

In another design application, it was necessary to extend two panels radially outward a short distance (approximately 7.62 centimeters (3 inches)) from the missile during boost flight. The mechanism worked in limited ground-based tests under simulated flight loads (accelerations) but malfunctioned in flight. Subsequent investigation and ground-based testing revealed a marginal design: the actuating spring was just barely strong enough (really, not quite strong enough) to overcome accumulated friction forces when under maximum g loadings. In the initial design, clearances were made generous, and the spring was thought to be stronger than necessary; thus, the friction problem was not addressed adequately. There was another contributing factor. The actuating rod was supported or guided by two nylon sleeve bushings. After the flight anomaly, the materials experts suggested that these bushings swelled under long (several months) exposure to a humid atmosphere and increased the friction. An "over-test" on the ground may have exposed the marginal nature of the design, but the test was not conducted until after the fact. Subsequently, design improvements were made to minimize friction.

To confirm the postulate that the hydrophilic property of nylon could have adversely affected the operation of the actuator, an accelerated moisture-absorption test was conducted by submerging the assembled actuator in a tank of hot water (333.15° K) for approximately 3 weeks. After soaking, the actuator would not function because the nylon bushings swelled to the extent that they squeezed the actuator shaft. Accordingly, Rulon C (a filled tetrafluoroethylene) was used in the bushings. Rulon C is unaffected by moisture and, in addition, has a lower coefficient of friction than does nylon. Quantitative measurements were made in a second accelerated moisture-absorption test in which bushings made both of nylon and Rulon C were soaked in hot water. Test results, shown in figure 4, are indicative that the wall thickness of the nylon bushings increased 2.5 percent, whereas the Rulon C bushings were virtually unaffected (actually shrank slightly). The original and new design configurations of the actuator are shown in figure 4.

Series Of Problems With Module Launcher

In this example it was required that a module be mounted in a launcher in an off-center position inside a spinning body and, upon signal, be ejected from the launch tube by means of a spring that provided both linear and rotational motion to the module. After a short delay (approximately 3 seconds), the module functioned. The rotational motion produced spin stability to provide a favored orientation for the module. This subsystem of module and launcher was tested during the development program, but in the first test, the module was not ejected properly. Subsequent investigations revealed a sequence of errors.

The launcher was simply a tube that had generous clearance so that friction was not considered to be a problem. Two factors were overlooked here: the module did not come out smoothly, but tended to chatter in its travel out of the tube; and the module had a safe-arm device which, it should be noted, was always in the "safe" position during development testing of the ejection mechanism. The safe-arm device used three spring-loaded steel balls that were ejected radially to actuate the module when it was free of the launch tube. In the "safe" position, the balls were constrained physically from moving by the safe-arm device but, when in the "armed" position, the balls bore against the side of the launch tube. Both of the factors just mentioned introduced friction; this fact probably accounted for the flight failure. Subsequently, improvements were made to reduce friction. These improvements included a redesign of the safe-arm device so that the balls were ejected by centrifugal force caused by the module spin rather than by a separate spring; thus, friction on the inside of the launch tube was largely eliminated.

During this development, ejection tests were conducted vertically downward to eliminate the effects of gravity on the tumbling motion of the module. In flight tests, the module was ejected in a gravity-free environment. This environment (that is, lack of gravity), incidentally, invariably complicates ground-based testing and often leads to errors. In arriving at the true separation velocity, the effect of the force of gravity was subtracted, which, in some cases yielded a negative separation velocity, clearly an impossibility. This proved to be a testing error: the ejection spring was found to be time dependent (as is any spring); thus, the module actually was falling away from the spring.

At first, the rate of tumble was thought to be negligible because it appeared to be so small in the short time it was observed in the test movies. More careful data reduction, however, indicated that the module would be pointing almost backwards when it functioned, showing that the tipoff moment was unacceptably large and the spin stabilization was inadequate. Two design changes, supported by additional analysis, corrected these deficiencies: a "zero-length" launcher was designed (the last point of contact of the module with the lip of the launcher was at the center of gravity of the module) and a "flywheel" was added at the longitudinal center of gravity of the module to increase its rotational moment of inertia.

In making these changes, the diameter of the launch tube was enlarged; thus, the tube no longer restrained the safing balls in the module so that they were free to fall or be jarred out by logistic and boost environments before the signal to eject the module. Unfortunately, this rather obvious mode of failure was not realized until after the flight test when module function was not obtained. As mentioned earlier, a given magnitude of spin was required to eject the safing balls. During the failure analysis, it was realized that transverse shocks and vibration experienced prior to module release could produce sufficient force to free the balls and cause the captive module to function. A fall-away collar was added to correct this problem. In final evaluation tests, in which the module with this collar was ejected in the atmosphere, the module still underwent an unacceptable rate of tumble. Even though the analysis indicated the aerodynamic loads were negligible, subsequent tests were transferred to the vacuum chamber, wherein successful ejection was obtained. In subsequent flight tests, the device worked successfully. The original and final design configurations are shown in figure 5.

SUGGESTIONS FOR MINIMIZING MISTAKES IN MECHANISM DESIGN

As is obvious from the foregoing discussion, the design and development of a mechanism is not generally a one man or even a one department undertaking, but involves three main activities: design, analysis, and testing. However, the predominant or leading role inherently falls to the design group. If the mechanism does not perform properly, the blame, either in full or in part, ultimately falls on the design; even if circumstances permit or are created to spread and obscure this blame, it is of little consequence because, in the majority of the cases, it is up to the design group to resolve the problem.

If it turns out that the analysis or testing efforts have not adequately supported the design, the blame must be shared by the design group for not making the proper requests or for not challenging or properly monitoring these support efforts. Even in matters defined as problems in quality control and manufacturing, design generally becomes involved. What then can the design group do to minimize the type of mistakes described?

The problems just described occurred in spite of the fact that each design was formally reviewed periodically by a design-review committee. Generally, conceptual, interim, and final design reviews were held. These reviews uncovered some, but obviously not all, the weaknesses in the design. It is felt that, in addition to these periodic reviews, a means to provide a disciplined, continuous monitoring of the design is

needed. It is proposed that this be done through a small control group within the design group; for lack of a better name, this group can be called the Design Parameters Group (DPG) and would be responsible to the design leader or supervisor. This group should be activated at the outset of any new design effort and one of its main functions would be to ask the right questions in a disciplined rather than haphazard way. To accomplish this, it is suggested that the DPG should establish the following documents or checklist for each design subsystem and should administer the checklists on a continuing basis. These documents are the tools designed to precipitate pertinent questions before the fact, so that potential problem areas can be revealed before the mechanism fails to perform in qualification testing or end-item usage. The functions of the DPG are shown in figure 6.

Design Parameters and Requirements Checklist

This checklist is a comprehensive list of the design requirements derived from systems and performance requirements. Many of these design parameters could be derived only with appropriate analysis, which would be done under the cognizance of the DPG. This list should be kept current as the design evolves and requirements change, and the list should be used as a checklist to ensure that the design meets each requirement. Then, a completed checklist should be manifested at each formal design review. An example of this checklist applied to the RAD is shown in figure 7.

Design-Limits Checklist

As is illustrated in the preceding examples, failures often occur because no effort was made to determine how marginal the design was. The design limits checklist would contain a definition and a list of the design limits; thus, design margins would be shown. Of course, this procedure is almost always done in stress analysis but not in functional aspects of the mechanism. In many cases, analyses and testing would be required in order to complete this list; thus, the list would be used to point out where additional analysis and testing should be done. A simplified example of a partial design limits checklist is shown in figure 8.

Test-Requirements Checklist

Test requirements should be generated by the design group and, indirectly, by the analysis group when test data are needed to supplement analysis. In conjunction with the administration of the design requirements, the DPG should prepare test requirements that would form the basis for test plans and requests. Then, the test results should be evaluated against the design requirements by the DPG. How such a checklist would be formulated is illustrated in figure 9.

Failure-Mode-Analysis Checklist

As soon as the design is defined sufficiently, the failure-mode analysis should be made by the DPG in conjunction with quality-control personnel. The failure mode analysis checklist consists essentially of a systematic listing of all postulated modes

of failure that could occur and a statement of what has or will be done to prevent failures or to ensure that failures cannot occur. This checklist should be kept current, updated with each design change, and submitted to the design-review committee. How this checklist could be applied to the RAD is shown in figure 10.

Why Won't It Work List

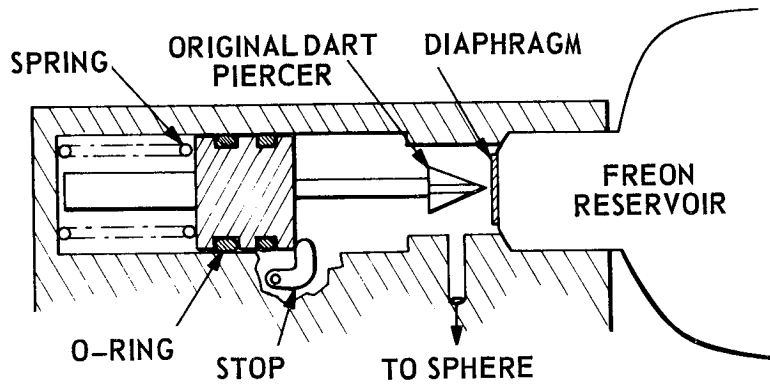
The critiquing engineer should list questions for each mechanism, asking what can or will keep the mechanism from working as intended; then, the critiquing engineer should obtain or provide the answers. Although this list will overlap the failure mode analysis checklist, it will supplement it by asking questions from a different viewpoint.

CONCLUDING REMARKS

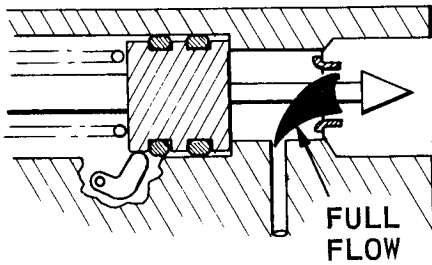
As was stated earlier, these checklists are intended to serve as tools to precipitate the questions that would uncover potential problems before the fact. To gain maximum benefit from the checklists, a proper or healthy attitude must be generated and maintained. Part of the task of the mechanism designer is to dispell the notion that "anybody can build a mechanism." The designer must convince critics (and helpers) that mechanisms are not so simple and trivial that development testing is not necessary. However, the designer has to develop a receptive attitude and guard against nurturing a defensive attitude. The designer should not be reticent in seeking expert help in specialized areas such as friction and lubrication problems and materials selection. Even in areas of his specialty, an independent review by other designers should not be discouraged.

REFERENCE

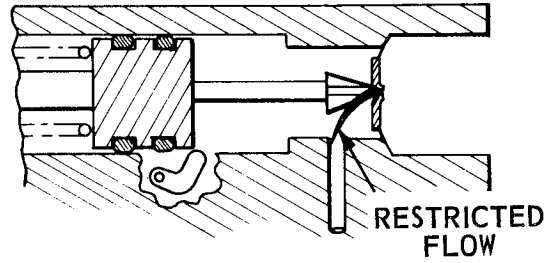
1. Riedel, J. K.: Radar Augmentation Device. Paper presented at the 6th Aerospace Mechanisms Symposium (Moffett Field, Calif.). NASA TM X-2557, 1972.



(a) Original valve assembly.

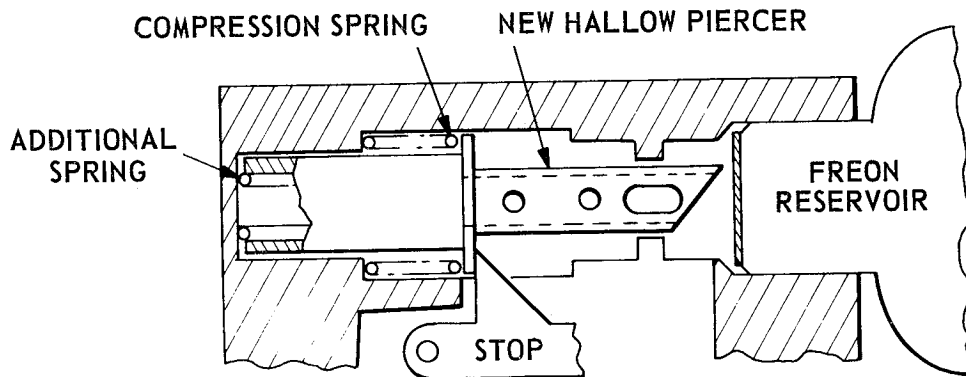


(b) Normal operation.

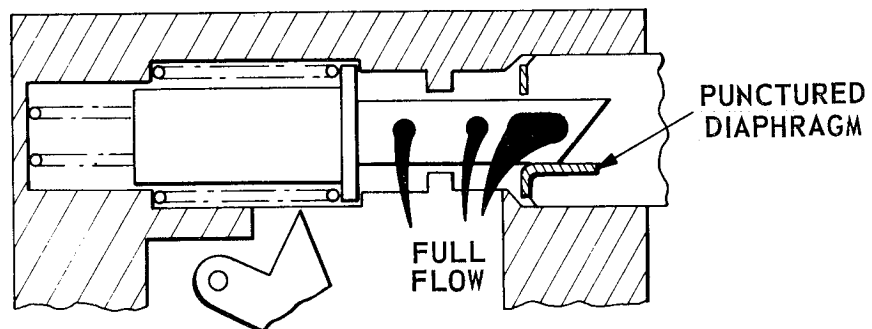


(c) Operation at elevated temperature.

Figure 1. - Illustration of the piercer problem.



(a) Cocked position.



(b) Fired position.

Figure 2. - Redesigned valve assembly.

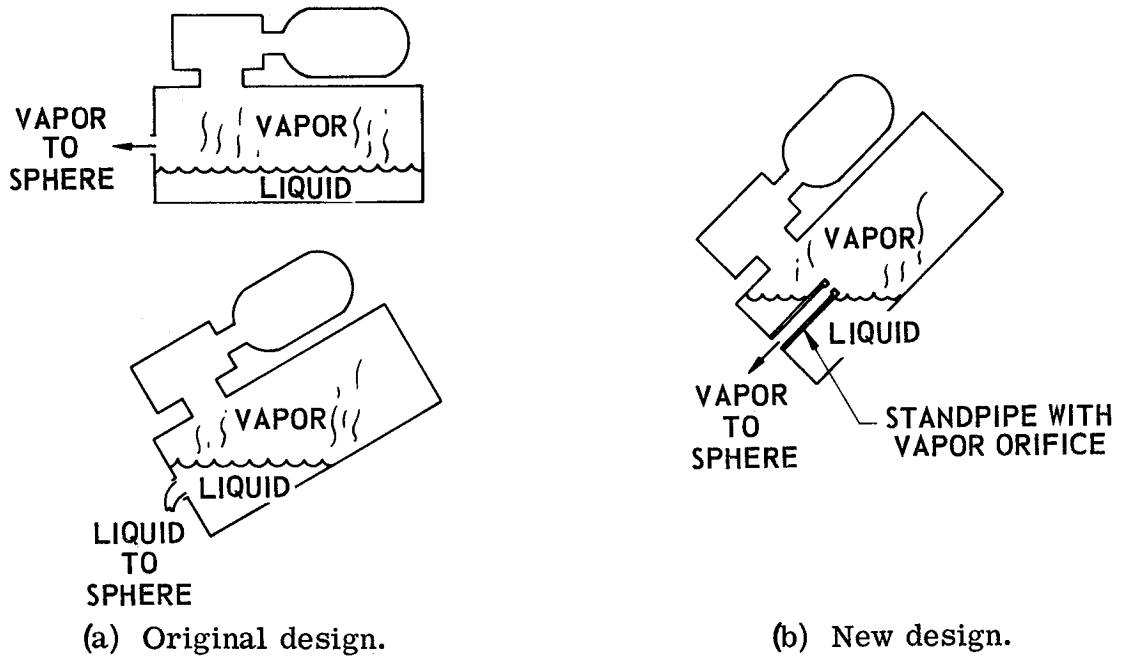


Figure 3. - Orientation problem.

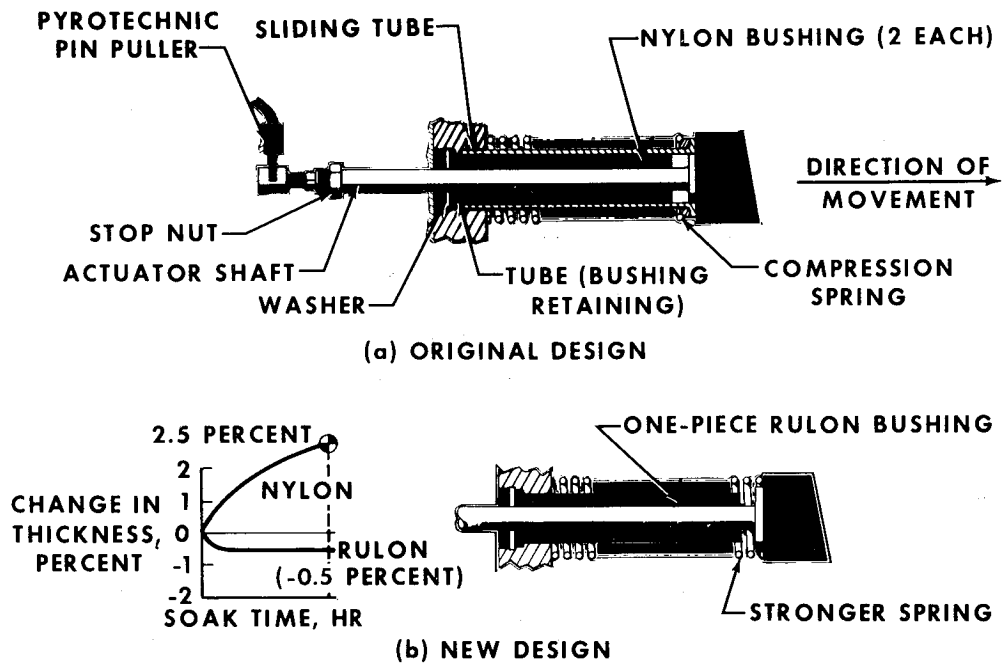


Figure 4. - Moisture-absorption problem.

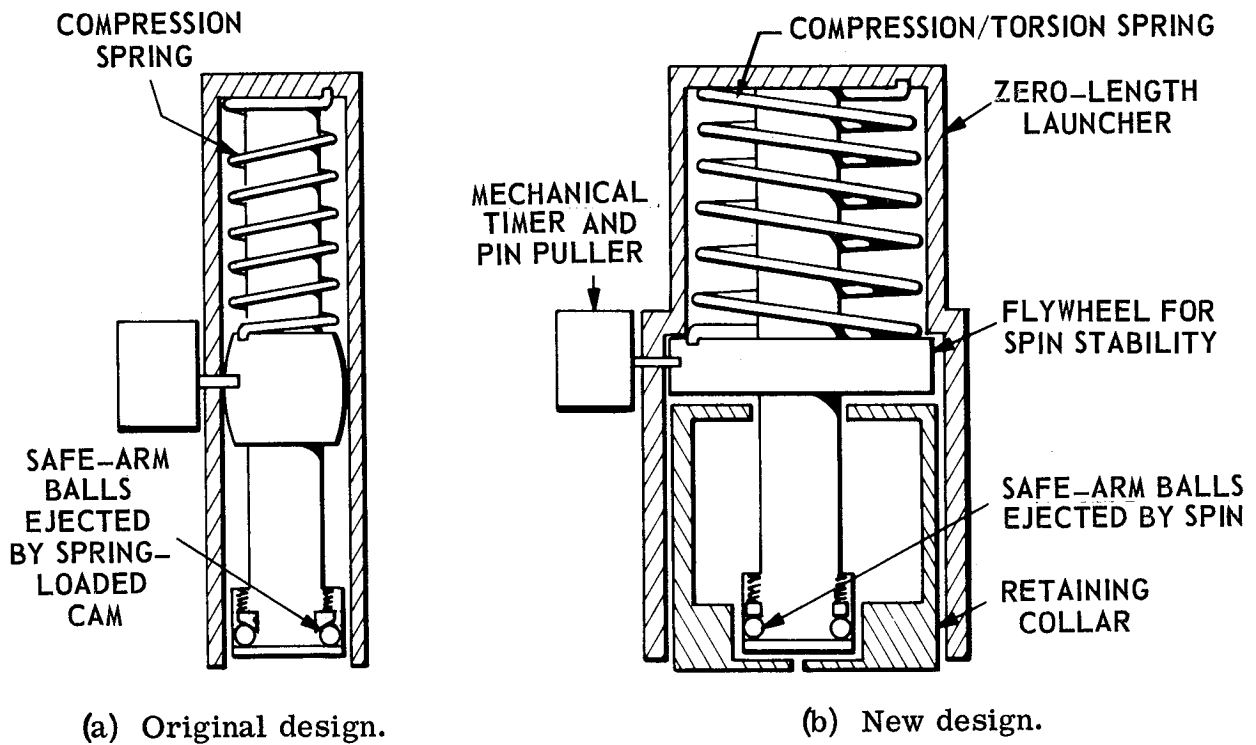


Figure 5. - Module-launcher problem.

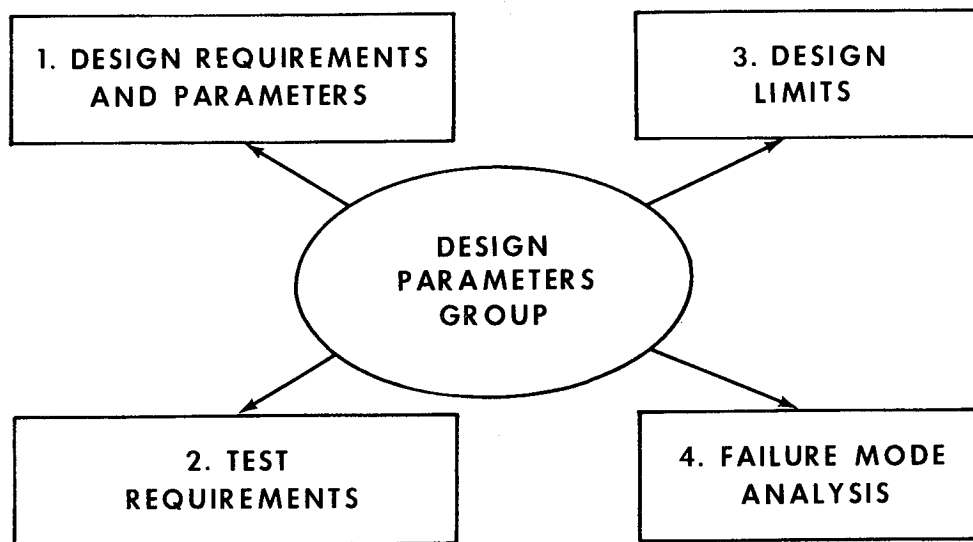


Figure 6. - Functions of the design parameters group.


SYSTEM REQUIREMENTS	DESIGN REQUIREMENTS	DESIGN SOLUTION
ALINEMENT (REACTION CONTROL SYSTEM) <ul style="list-style-type: none"> ● PASSIVE DEVICE ● DEPLOY FROM RIGHT-HAND EQUIPMENT BAY ● 1m² MINIMUM 	LARGE REFLECTOR SELF-ERECTING STEADY (REACTION CONTROL SYSTEM)	 <ul style="list-style-type: none"> ● 8-FT SPHERE ● ALUMINUM ● SMOOTH SURFACE
TETHER TO RIGHT-HAND EQUIPMENT BAY	RAPID INFLATION ORDERLY UNFURLING	2-SEC FULL INFLATION ACCORDIAN AND PLEAT FOLDS
DISAPPEAR DURING ENTRY	CONSUME BY ENVIRONMENTS	NO METAL STRUCTURE MYLAR SKIN

Figure 7. - Design-requirements checklist.


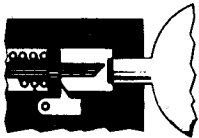
PARAMETER	LIMIT
RATE OF INFLATION SPIN 	DETERMINE BY TESTING <ul style="list-style-type: none"> ● MINIMUM RATE, TWIST AND TANGLE ● MAXIMUM RATE, TEAR OR BURST VARY SIZE OF ORIFICE
PIERCER PENETRATION 	DETERMINE MAXIMUM PIERCING CAPABILITY <ul style="list-style-type: none"> ● TEST PROGRESSIVELY THICKER DIAPHRAGMS TEST TO FAILURE OR MAXIMUM

Figure 8. - Design-limits checklist.




COMPONENT	TEST REQUIREMENT
PIERCER MECHANISM	TEST SPRINGS BENCH TEST PIERCER PENETRATION FUNCTIONALLY TEST IN SYSTEM TEST
	
TETHER EXTENSION	TEST VOLUTE SPRINGS FUNCTIONALLY TEST IN EXTENSION VACUUM WITH FREON
	
SPHERE INFLATION	LEAK TEST , AND SO FORTH
	

Figure 9. - Test-requirements checklist.




COMPONENT	ASSUMED FAILURE MODE	CAUSE	DESIGN ACTION
PYROTIMER 	DOES NOT CUT PIN	<ul style="list-style-type: none"> ● PYRO ELEMENT FAILS ● PIN IS TOO HARD 	PREVIOUSLY QUALIFIED <ul style="list-style-type: none"> ● OVERTEST ● INSPECTION
TETHER 	NO EXTENSION PARTIAL EXTENSION	LINKAGE DOES NOT RELEASE LID <ul style="list-style-type: none"> ● HIGH FRICTION ● INSUFFICIENT CLEARANCE 	<ul style="list-style-type: none"> ● TOLERANCE STUDY ● VERIFY IN TEST ● LUBRICATE ● TOLERANCE STUDY ● INSPECTION POINT
PIERCER 	DOES NOT PUNCTURE DIAPHRAGM	<ul style="list-style-type: none"> ● NO RELEASE ● WEAK SPRING ● AND SO FORTH 	VERIFY IN TEST 100 PERCENT TEST

Figure 10. - Failure-mode-analysis checklist.

