Mechanism Design—A Test Laboratory Viewpoint

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The test laboratory can be a valuable resource for the mechanism designer, especially in determining environmental requirements, cost estimates for test phases, clues to design pitfalls, and data references for tests of similar mechanisms. The designer should carefully define in writing the functional and environmental requirements for the item he is designing. He should also be aware of the "personality problems" (binding, galling, and fusing) of moving parts.

I. Introduction

The service test laboratory has a unique vantage point for viewing company operations. First of all, it participates in almost all contractual activity which involves hardware, and, secondly, it usually is not predisposed to the goals or philosophies of any one program or group. This second factor is important, since the test laboratory must function as an unbiased agent in providing support to engineering, manufacturing, and product assurance.

In this service capacity, the laboratory is afforded a broad and uncluttered view of what is happening. It frequently is in a position to provide constructive comments concerning both hardware and nonhardware factors. However, the basic function of the test laboratory is simply to subject the hardware to prescribed functional/environmental requirements and present the results. Seldom is this organization asked to evaluate or draw conclusions concerning the quality of the design or manufacturing process. Despite this operational mode, the laboratory does become exposed to quality factors. It sees the successes and failures, the good and bad designs, and the good and bad manufactured products. The purpose of this paper is to present laboratory observations gained from this vantage point as they concern the design process and offer a set of suggestions to the mechanisms designer.

II. Two Sets of Requirements

Before the designer of an aerospace mechanism can proceed with his work in depth, two sets of requirements must be established. One set is general and the other set specific. The general set presents the mission objectives and the controlling overall environmental specifications, whereas the specific set identifies the functional purpose and use habitat of a particular part or assembly. In theory, both of these guidelines should exist well in advance of full-blown efforts to design the hardware. Normally this condition is true for the general set; however, advanced availability for the specific set is the exception rather than the rule.

III. The Stability of General Requirements

General requirements of the program are essentially based upon mission objectives which are fixed by the customer after many months and sometimes years of research, engineering studies, and conceptual designs. Once defined and released to the contractor, the mission objectives remain relatively stable. Major changes in their scope or timing are uncommon, since these events have an impact on the national budget, and, therefore, may involve congressional approval.

An important part of the general requirements is a specification which prescribes overall environments. The content of this document is determined by the characteristics of the launch booster and the use habitat. Here, again, the decisions of long-range planning will apply, since they set forth the launch vehicle, the "on station" mode, and the reentry phase if there is one. Major changes in these areas, after contract award, are indeed rare and, if they occur, generally constitute grounds for schedule and cost redirection.

For the most part, the booster is selected from an available inventory of proven vehicles for which performance/environmental characteristics are well known. It is infrequent that a new booster and payload evolve simultaneously with the resultant necessity to predict system characteristics based upon wind tunnel and other tests. For space vehicles and ballistic missiles, the launch booster dictates environments of the ascent profile, with particular attention to dynamics of vibration, acceleration, pressure and thermal exposure. Usually, the ascent phase constitutes the greatest challenge for payload survival, particularly in areas of mechanical environments. However, certain reentry payloads are an exception, since the mechanical conditions are sometimes more severe during that phase.

It is accepted that environmental requirements will vary considerably between space vehicles and ballistic missiles. Examples of the variations are the long-term exposure to the unfriendly conditions of deep space experienced by an orbiting vehicle or space probe as compared with the defensive measures exercised against a missile warhead. However, regardless of the program type, the general environmental requirements are broad and concern the common needs of the total vehicle rather than specifics.

IV. The Dynamic Character of Specific Requirements

The specific requirements for each identifiable assembly, subassembly, and even, sometimes, each part, are normally enumerated by the design control document. For future reference, I will call this document the Design Control Specification (DCS). The intent of the DCS is to prescribe the functional/environmental requirements of proposed hardware for the purpose of guiding the individual designer. It seldom achieves this objective, since it usually does not exist in a released and approved state at the time that the designer needs the information to begin his work. Even if an early release is achieved, the first publication rarely establishes the final requirements. There is a practical reason for this condition, which is recognized by the individual designer: the requirements for aerospace vehicles, in total or in part, seldom are static during the design phase, particularly during the conceptual period. As a consequence, the DCS will be revised throughout the life of the program. The number of revisions is higher in the early stages, and the paperwork system often falls behind in documenting this reality of evolving requirements. During the preliminary and conceptual phases, many changes are not even introduced into the documentation network, but are left to accumulate for a later group updating.

As a test laboratory, we have experienced instances where the prototype specimen is fabricated and available, the design is in blueprint form, and yet the DCS has not been released. In some cases, the best document that is available is a red-lined mark-up of a comparable document from another program, or an unreleased final draft. This condition does not reflect a disregard for configuration control. Nor is it peculiar to any one company. It is an industry-wide problem that is inherent in the nature of the programs undertaken. The underlying causes can be traced to factors such as the first-time aspect of the mission; the complexity of the project, encompassing both hardware and software; the need to perform concurrent development and sometimes invention; schedule squeeze; and the inertia of the contractual paperwork system.

In view of these realities, it is essential that the mechanism designer exercise a good deal of judgment and communication with his many interfaces when attempting to interpret and apply the DCS. This includes other designers responsible for mating hardware and utilities, and support engineering agencies such as those concerned with stress, thermal conditions, and weights, to mention a few.

V. The Unpublished Guideline

The ultimate objective of any mechanism design is to provide a device that will balance technical, cost, and schedule factors with the mission objective. To do this, it must supply the needed function, perform adequately under exposure to the use habitat, satisfy the life requirements, incorporate simplicity, and achieve an economic balance considering its own cost to produce and its impact upon associated hardware and systems.

Indeed, this is a worthwhile objective and an oversimplification of a real challenge. Considering this difficult goal and the generally unavailable state of the DCS, the first thing that the designer should do is to carefully evaluate and define in writing the functional and environmental requirements of the hardware for which he is responsible. The scope of this action will vary, depending upon each situation; however, it is recommended that this be an unpublished document prepared in outline form. It should record the current and realistic requirements as recognized by the prime parties concerned. An early-release DCS is a starting point, but a designer should not rely completely on this source, since it often may prescribe needs that are outdated by the inability of the paperwork to keep pace with a fast-moving program. It is especially recommended that the designer go beyond those boiler plate functional/environmental callouts of the DCS to specify intimate factors that are peculiar to the individual mechanism.

Each part to be designed has a personality all its own as dictated by its particular functional requirement and use habitat. For this reason, it is often dangerous to accept the total vehicle or even subsystem parameters as all-encompassing. In contrast to black boxes, most mechanisms have special needs to be considered: namely, the inherent features of displacement and motion. These features introduce new dimensions to interpretations of environmental and functional specifications. They place added emphasis upon evaluating hardware performance under conditions such as zero gravity, mechanical vibration, high vacuum, and temperature extremes. Many designers have learned from experience that moving parts of mechanisms, in contrast to fixed assemblies, have "personality problems" that are often exhibited by the binding, galling, and fusing of moving parts. These unique personality problems of mechanisms must be recognized early in the design and integrated into the development plan. If the DCS is inadequate, then the working guideline must specify these factors as appropriate to the particular device in question.

Now another comment from the laboratory viewpoint. At an early point in establishing the design plan, the designer would do well to contact the test laboratory and obtain leads concerning like mechanisms that have undergone development and qualification testing. He can then be directed to test reports that record in detail the experiences of similar hardware. These documents describe the test specimen, the environmental exposures, the functional requirements, and the results.

However, this screening process should not be restricted to in-house operations. Sometimes it is advantageous to undertake a literature search of similar mechanisms designed and tested by others in the industry. The government data bank of the Defense Documentation Center can be of value in this regard. The individual technical libraries are aware of these sources and know how to interrogate the data banks. Results of these contacts and discussions will frequently supply valuable information concerning the successes and failures of others, as well as furnish reliable cost data for testing. Also, these contacts will help to compensate for the natural tendency of designers to be optimistic concerning the ability of their creations to pass the testing phase. It is expected that the content of the working guideline will be influenced by the findings of this communication.

Once the working guideline and plan have been established, the individual designer has at least the latest basis upon which to proceed. Furthermore, he personally can keep this requirements paper up to date by his own editing, since it does not constitute part of the formal documentation process. This work sheet will also provide a good foundation for eventual updating and final release of the DCS. A written trail will exist from first conception through to the last configuration.

VI. Conceptual Work

Now, with latest requirements documented and coordinated, the designer can direct his full attention to the hardware. He can, with reduced risk, proceed to resolve the geometry and the selection of materials and parts. Certainly, downstream changes will occur, but at least action has been taken to avoid those major surprises that arise from lack of adequate preparation and coordination.

As the design starts to take final form, the designer should contact the test laboratory again for an informal critique, at a point where the design is well conceived but not yet frozen. There is a definite logic to this proposed second communication with the testing personnel. Generally, the assigned engineer has not been responsible for the design and testing of all similar mechanisms for a variety of projects within the company. Furthermore, in a large company, he seldom has personal access to the multiplicity of designers who have engaged in such endeavors. However, the laboratories in the company usually have been exposed to all these mechanisms and the testing personnel have first-hand knowledge concerning some do's and don'ts.

Generally, only one contact of this type is necessary, since most companies do not duplicate the laboratory function, because of the expense for equipment and special facilities. Personnel who staff these laboratories have had painful experiences that will be most helpful to the individual designer in an objective critique of the conceived approach. At the very minimum, such a critique can assure the designer that he does not expose himself to the known pitfalls of others.

VII. Development of the Hardware

After the design comes the testing of the hardware, both prototype and end-item configuration. Two phases of testing normally occur – the first concerned with evolution of the design and the second with formal proofing of the final product. Both of these phases should encompass functional and environmental aspects. Again, from a laboratory viewpoint, it is our experience that the maximum emphasis of the designer in the development phase tends to focus on the functional requirement. Environmental factors are considered in catalog selection of the parts that go into the assembly, but actual environmental confirmation of these parts and prototypes of subassemblies is, for the most part, deferred until the qualification phase. Herein lie the seeds of disaster. As design problems are encountered in the qualification test program, two factors work against implementation of the best solution. One is time, and the other is the packaged state of the configuration.

Speaking from experience, I cannot emphasize too strongly that all unproven parts and subassemblies should be thoroughly evaluated under the use environment before final incorporation into the mechanism design. For outside-purchased parts, the responsible designer should be careful of interpreting or extending vendor performance data. Remember that the vendor's fact sheet is primarily marketing-oriented. Sometimes the performance data may be optimistic and not fully supported by test exposure. To protect himself, the designer should not hesitate to ask the vendor for the results of his test program. Even here, caution must be exercised, since the test data might not consider the effects of combined environments, life expectancy, or mounting orientation. If possible, as the design is evolved, prototype subassemblies and assemblies should be subjected to selected environmental conditions of the use habitat. Breadboard and bench evaluations of the mechanism from a functional viewpoint are only part of the assignment. Neglect of the complementing environmental exposure constitutes a gamble.

This expansion of environmental testing in the development phase costs money, but it certainly has economic and other advantages over incorporating a fix under conditions of a schedule panic, or loss of a multimillion dollar vehicle at launch, or loss of data from "on station" due to malfunction of an "insignificant" part or mechanism. This recommendation is not a make-work program for the test laboratory. It is a recommendation born of experience. Let me cite one example of a qualification failure that could have been avoided by an adequate test program in the development phase.

Figure 1 depicts a payout cable mechanism used in one of the *Agena* configurations. Its function is to supply an extended electrical connection between the booster and *Agena* vehicles during the separation sequence. As the *Agena* moves away from the booster on a rail system inside the booster adapter, the stowed cable is fed out at a rate of 5.5 ft/s. When the cable is fully extended and the *Agena* has cleared the booster adapter, then the force from the displacing masses is applied through the cable to the mating connectors. This pull force engages a mechanism in the *Agena* mating connector which causes disengagement of male and female segments and

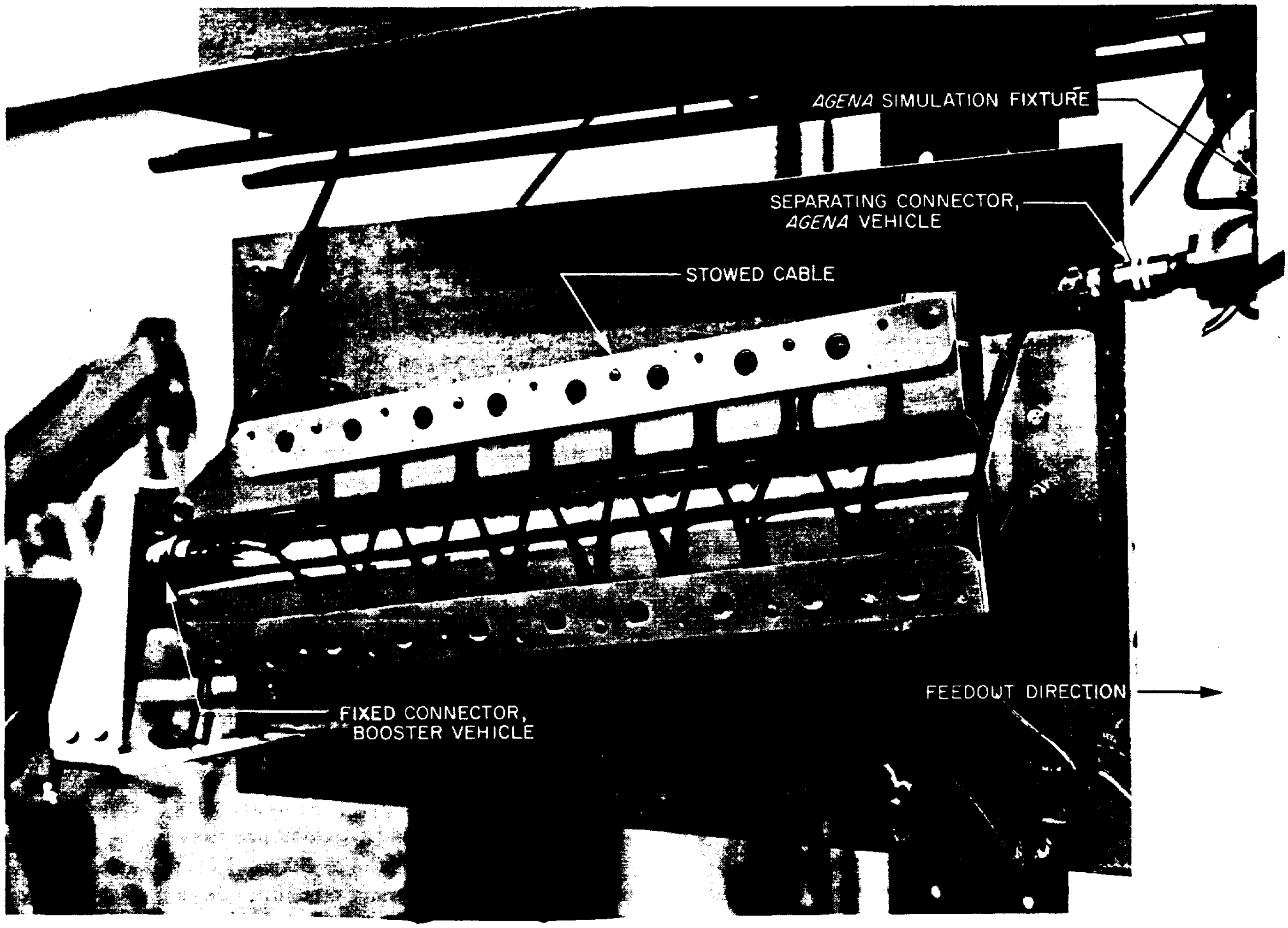

Fig. 1. Payout cable installed in functional test fixture (top cover off)

release of the two vehicles. Magnitude of the load necessary to activate the separation device was established at 15 lb maximum. The amount of pull required was considered important because of the unwanted effect of a higher load requirement upon the orbit path. This assembly ensures that if a hang-up occurs in the slide-out phase, then the extended electrical connection will permit destruction of the total complex if necessary. Two mechanisms are involved, one for stowing and guiding the cable, and a second for disengaging the *Agena* mating connector.

The assembled specimen was submitted for qualification without the benefit of a prior development test. The specification called for exposure to mechanical environments of acceleration, shock, and vibration, with functional tests before and after each environmental condition. The delivered specimen was installed in a test fixture that simulated the exit motion of the *Agena* from the booster assembly. This fixture was designed to duplicate the mounting orientation of the payout assembly and supply the prescribed motion rate and force load to the *Agena* end connector as the cable was deployed.

In the first functional evaluation, the cable jammed in the housing. It did not extend even when a pull force in excess of 100 lb was applied. To correct this situation, several design changes were made in the housing. These changes provided greater clearance in the relationship of the stowed cable and the feed-out guides. The reworked specimen then passed the pre-environmental functional test in accord with the specified feed-out rate and pull force.

As the first environmental exposure, the specimen was subjected to several levels of steady-state acceleration.

While the specimen was under acceleration load, electrical continuity was uninterrupted and the cable retained a packaged position. A post-environmental functional test was performed, and the system worked as required. The next environmental exposure was a shock condition. All proceeded well during this environmental condition, and the subsequent functional test was satisfactory.

Finally, the assembly moved to the vibration environment. The vibration fixture and specimen mounting were designed in a manner that simulated the vehicle configuration. With this setup, the specimen was exposed to the prescribed vibration loads. Here, again, electrical continuity was satisfactorily maintained during the environmental exposure. Afterward, the specimen was removed from the shaker and installed in the simulated vehicle fixture to perform a post-vibration functional test. The cable fed out as required, but the *Agena* connector failed to disengage at the fully extended cable position and the prescribed pull load. A visual inspection of the connector revealed galling and pitting of the race and ball mechanism which activated the male-to-female release. Further testing established that a force of 121 lb was necessary to achieve disengagement, as compared with the design requirement of 15 lb maximum.

Since time did not permit the search for a new separating connector, action was taken to decrease the vibration level experienced by the component. After several changes in the mounting arrangement, an improvement was made. As a result, the galling and pitting problem was minimized, and separation of the connector was obtained at a pull force of 21 lb. These corrections were made after a series of vibration exposures in different mounting configurations.

The improved performance of the connector still was considered marginal and, therefore, a backup separation approach was begun. The backup system was based upon a failure of the conductor strands at the point of attachment to the connector housing. This safety arrangement was to take over only if the connector failed to disengage. A series of destruct tests was run to determine the load requirements for break-away of the conductors from the plug attachments. Findings indicated that with a multistrand cable of equal conductor lengths, the force was well in excess of 100 lb. A load of this size was not acceptable because of the effect upon the orbit path. To correct this situation, the electrical conductors were assembled in varying lengths so that the pull force would be applied to each strand, one at a time. This change lowered the force requirements to within acceptable limits. In actual flight, the modified system functioned well, and a clean separation was obtained.

Although, on the surface, the payout cable mechanism appears to be relatively simple, the qualification test program ultimately involved three development efforts. These included a first effort for functional payout of the cable, a second for mounting orientation of the connector, and a third for establishment of a backup release system. In addition to the specimen requirements, a moderate development program was necessary to de-bug the test fixture which simulated speed and pull force of the deploying *Agena* vehicle.

This qualification test was originally estimated at 1215 manhours and was expected to be complete in 3 weeks. In the final process, the test effort required an expenditure of 3076 manhours, and a time period of 6 weeks. Compounding the situation were extreme pressures for resolution, since the flight schedule was rapidly approaching.

The purpose of this example is to demonstrate that even in the simplest devices, there can exist unexpected complications. These complications are magnified when they are encountered for the first time in a qualification test program. A development test program encompassing both functional and environmental factors is a sound investment in the long run: it minimizes the chance of a major failure during the formal qualification demonstration, and it protects against those unplanned expenses that occur when a major redesign must be developed and incorporated as the flight date rapidly approaches. I am sure that all of us have experienced the disappointments of a last-minute test failure and recognize the problems that result in cost, strained customer relationships, internal organizational conflict, and personal pressures. To minimize these prospects, a good design plan must be prepared early, and it must contain an adequate test program.

VIII. Summary

In summary, I would like to offer the following suggestions:

(1) Establish design requirements for the individual mechanism in writing before proceeding with

conceptual work. Consider both functional and environmental factors. Do not depend upon the availability of a DCS document. If a DCS is available, do not accept its content as the current requirement without checking.

(2) Take steps to identify those highly personal needs of each mechanism. Thoroughly sort out potential problems introduced by the factors of motion or displacement peculiar to your mechanism.

(3) Don't be reluctant to turn to the test laboratory for assistance in determining the environmental requirements, cost estimates for test phases, clues in design pitfalls, and data references for tests of similar mechanisms.

(4) Place maximum emphasis upon functional and environmental testing during the development phase in order to avoid cost disadvantages and embarrassment associated with a failure during qualification.

In conclusion, the test laboratory organization is a source of knowledge and experience which can be valuable to the individual designer. Unfortunately, these talents are rarely tapped in the planning, design conception, or development test phases. As a consequence, in many companies the test laboratory functions almost exclusively as a qualification shop rather than an arm of engineering and design. I urge the mechanism designer to take advantage of this available knowledge and make the laboratory a contributing partner in the design.