BY ORDER OF THE COMMANDER

SMC Standard SMC-S-004
13 June 2008

Supersedes:
New issue

Air Force Space Command

SPACE AND MISSILE SYSTEMS CENTER STANDARD

INDEPENDENT STRUCTURAL LOADS ANALYSIS

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

FOREWORD

1. This standard defines the Government's requirements and expectations for contractor performance in defense system acquisitions and technology developments.

2. This new-issue SMC standard comprises the text of The Aerospace Corporation report number TOR-2003(8583)-2886.

3. Beneficial comments (recommendations, changes, additions, deletions, etc.) and any pertinent data that may be of use in improving this standard should be forwarded to the following addressee using the Standardization Document Improvement Proposal appearing at the end of this document or by letter:

Division Chief, SMC/EAE
SPACE AND MISSILE SYSTEMS CENTER
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245

4. This standard has been approved for use on all Space and Missile Systems Center/Air Force Program Executive Office - Space development, acquisition, and sustainment contracts.

James Horejsi, Col, USAF
SMC Chief Engineer

Contents

Figure

1. Introduction

During launch and ascent, a spacecraft and its launch vehicle experience severe structural loads. These loads represent the principal design requirements for most of the launch vehicle and spacecraft structure. Critical load-producing events include liftoff, atmospheric flight (static aeroelastic, gust/turbulence, buffet and other load contributors), engine ignitions and shutdowns, and staging and separation events.

The structural design and validation process involves independent contractors and organizations, and numerous technical disciplines such as structures, structural dynamics, fluids, propulsion, controls, flight mechanics, statistics, and atmospheric sciences. The determination of structural dynamic properties, loads, stresses, and structural margins of safety requires specialized testing, extremely large mathematical models, and complex analyses. Significantly complicating the process is the fact that the fully integrated spacecraft/launch vehicle system needs to be addressed, and the integrated system cannot be tested prior to flight. Further complications arise because significant engineering judgment is involved, no single organization controls the overall structural dynamic properties of the integrated system, and schedule and cost considerations play major roles.

Launch and ascent structural loads are functions of the dynamic properties of the integrated spacecraft/launch vehicle system. Therefore, design changes in one element can result in load changes in all elements, and modeling errors in one element can result in load prediction errors in all elements. Because the dynamic properties of each element depend upon the structural design of that element, the design and analysis process is iterative.

As a result of the above considerations and lessons learned, a formal Load Cycle Process was developed for use on Air Force programs (Fig. 1, Refs. 1 and 2). In 1979, the requirement to follow this process was levied on both the spacecraft and launch vehicle program offices by SAMSO Regulation 550-5, Commander's Policy on "Independent Structural Loads Analysis of Integrated Payload and Launch Vehicle Systems" (Ref. 3). SAMSO Pamphlet 800-5 (Ref. 4), developed in 1975, was specified in the Commander's Policy to aid program offices in implementation of the policy. The policy was suspended in the nineties as part of the government effort to reduce military specifications.

SAMSO Regulation 550-5 provided uniformity in the structural design and evaluation of both spacecraft and launch vehicle structure, and can be credited to a great extent with the success of the structural systems within its purview. It also helped ensure that all involved parties understood their responsibilities to each other, and minimized the potential impacts to the government when problems arose. Since suspension of the regulation, a number of issues have arisen. These are addressed herein as an updated version of SAMSO Pamphlet 800-5 that retains the principal ingredients of the original document and accounts for lessons learned since the time it was written. The intent of this document is to serve as a source of requirements for implementation of the Load Cycle Process and its most critical elements.

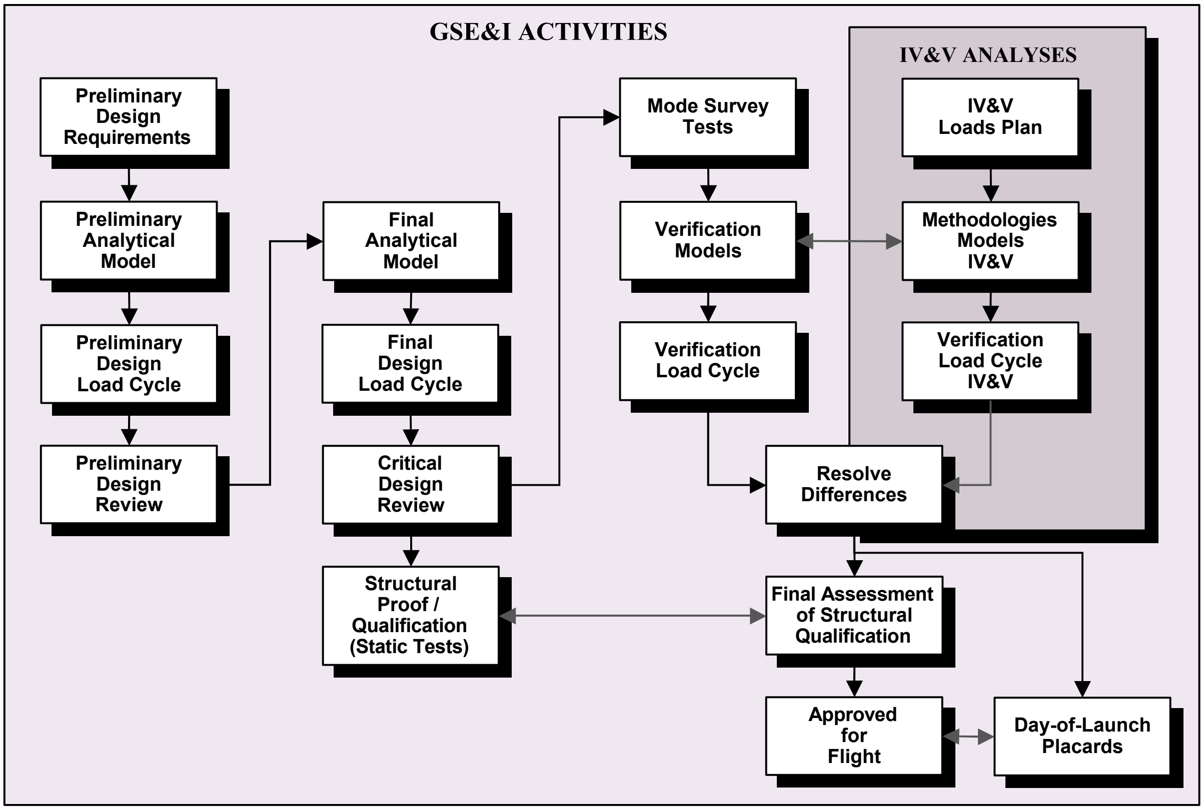

Figure 1. The Load Cycle Process (GSE&I - General Systems Engineering and Integration; IV&V - Independent Verification and Validation)

2. Background

Loads occurring during vehicle launch and ascent are among the principal factors in establishing the requirements for structural design and verification of a spacecraft and its launch vehicle. Determination of these loads requires comprehensive, complex analyses of the dynamic response of the integrated spacecraft/launch vehicle system caused by the excitations arising during launch and flight. Timely determination of these loads to effect orderly design evolution requires careful planning and execution of these analyses by a designated loads contractor.

The significance of launch and ascent loads to the structural integrity of the spacecraft and launch vehicle is emphasized by the Load Cycle Process (Fig. 1, Refs. 1 and 2). Implicit in this process is the recognition that for each program there is a loads contractor, typically the launch vehicle organization, who generates primary loads information as required for normal launch vehicle and spacecraft development. The loads contractor's final Verification Load Cycle prediction of loads supersedes all earlier predictions and forms the basis for commitment to flight. Because of its criticality and past experience, this final prediction of flight loads must be validated by an independent source.

Successive sections of this document define the constitutive parts of a loads analysis. These include: the procedure for acquisition of primary launch and ascent loads information in a manner compatible with program schedules and milestones; the criteria to be met by the independent loads analyses; management of, and data requirements for, the independent analyses; and program-peculiar considerations in prescribing the scope of the independent analyses.

The approach described herein has been successfully applied to the determination of launch and flight loads for a large variety of sophisticated launch vehicle and spacecraft structure developed under Air Force management.

3. Dynamic Loads Analysis Procedure

Structural design and test of launch vehicles and spacecraft require knowledge of the forces to which they will be subjected in their operational environment. These forces are usually termed external loads or forcing functions. The corresponding internal loads arising from the transient responses of the spacecraft/launch vehicle system to these external disturbances are of critical importance. A number of events involving the sudden application or removal of large external forces to the launch vehicle occur during launch and ascent. All should be investigated for their potential criticality to the launch vehicle and spacecraft structure.

Loads depend on the following elements:

- **The dynamic characteristics of the spacecraft.** These may be described in terms of their natural frequencies and their associated mode shapes, interface compliances (often referred to as constraint modes), damping values, and mass distribution.

- **The dynamic characteristics of the launch vehicle.** These are described similarly.

- **The dynamic interaction of the spacecraft and launch vehicle.** This involves the characterization of the coupled spacecraft/launch vehicle system properties by coupling the spacecraft and launch vehicle models described above. Unique models are developed for each flight event considered.

- **The externally applied stimuli, or forcing functions.** Typically, these include engine ignition and shutdown transients, launch pad interface forces, ignition overpressure pulses, ground winds, and aerodynamic disturbances such as static-aeroelastic loading, atmospheric turbulence (gust) and buffet.

A loads analysis involves:

- **Generation of a structural dynamic model of the spacecraft, typically by the spacecraft contractor.** The model is initially developed analytically using weight and stiffness data computed from design drawings. The model is then updated primarily by means of a mode survey test, whereby a spacecraft with flight-quality structure and mass simulated components is excited, and modes are determined from the resulting vibrations. Often, the dynamic properties of liquid propellants (slosh) must also be included in the model. Damping values can only be determined experimentally. Therefore, until a mode survey test is performed, historical data must be used. Unless justified by existing data, one percent of critical should be assumed for each mode.

- **Generation of structural dynamic models of the launch vehicle for each flight event, typically by the launch vehicle contractor.** These models are developed analytically using weight and stiffness data computed from design drawings and the propellant loading appropriate to the flight event under investigation, and are adjusted to be in accord with static and mode survey test data and any available measurements made on prior flights of the vehicle. Damping values can only be determined experimentally. Therefore, until a mode survey test is performed or flight data becomes available, historical data must be used. Unless justified by existing data, one percent of critical should be assumed for each mode.

- **Integration of structural dynamic models of the spacecraft and launch vehicle.** By analytically combining the spacecraft model with that of the launch vehicle, as configured at the time of each flight event, structural dynamic models of the ascent spacecraft/launch vehicle systems are formed. The integration of these models should preserve the three-dimensional motion that characterizes the dynamic behavior of the coupled spacecraft/launch vehicle system. The coupled system damping properties need to preserve any resulting coupling between modes, unless demonstrated for the system under consideration that the effect of the coupling is negligible.

- **Generation of forcing functions for each flight event.** The external forces acting on the launch vehicle are derived from flight data obtained on prior flights, from ground test data, or are developed analytically if no data is available. Atmospheric turbulence forcing functions may be extracted from measured winds; if this data is not available, a 30 ft/sec, one-minus-cosine waveform tuned to the low frequency system bending modes should be used. Buffet forcing functions can be obtained from wind tunnel test data if flight-derived functions are not available. Wind tunnel tests should also be used to define the aerodynamic loading/distribution needed in the static aeroelastic and gust/turbulence loads analyses. For engine ignition and shutdown events, families of thrust transients should be used so that the variability in thrust transients can be accounted for by statistical analysis of the resulting responses.

- **Calculation of structural dynamic responses of the integrated spacecraft/launch vehicle system to each flight event by applying the appropriate forcing functions.** For the liftoff event, the nonlinearities associated with the launch vehicle separating from the pad must be included in the calculations, and for the atmospheric flight events the engine side forces due to the autopilot response must also be included. These computed responses provide the accelerations, velocities, and displacements of the launch vehicle and spacecraft at specific nodal points of their structural dynamic models. All calculations are performed to statistical response enclosure levels with an associated confidence level defined by the customer. If not defined otherwise, loads should be computed to a 99.7 percent enclosure, 90 percent confidence level.

- **Determination of structural loads from calculated responses.** The accelerations, velocities, and displacements of the individual masses of the launch vehicle and spacecraft, and any applicable external forces are combined, via load transformation matrices, to provide the internal loads in structural elements. The full mode acceleration approach of load and displacement recovery is to be used unless it is demonstrated for the system under consideration that another approach will yield equivalent loads and displacement.

4. Loads Analysis Plan

Spacecraft and launch vehicle loads are dependent on the vibratory characteristics stemming from their structural designs. The structural design of the spacecraft and launch vehicle, however, are dependent on the loads they must sustain. Because of this interdependency, flight loads cannot be predicted precisely until the final design is established. This leads to iterative loads analyses during the launch vehicle and spacecraft design evolutions. Each iteration is called a load cycle. Three load cycles are usually sufficient. These are generally referred to as:

- **Preliminary Design Load Cycle.** The initial analytical model of the spacecraft is based upon the design established by Preliminary Design Load Factors together with any program-peculiar minimum stiffness requirements. Preliminary Design Load Factors are defined as simultaneously applied linear and rotational accelerations of the spacecraft about orthogonal axes. These are chosen early in the program and are estimates based on experience. These factors are best derived by an organization with insight into both sides of the spacecraft/launch vehicle interface. The Preliminary Design Load Cycle is intended to identify spacecraft design-peculiar effects and major strength deficiencies associated with the initial design established by the Preliminary Design Load Factors. The Preliminary Design Load Cycle should be completed by the time of the Preliminary Design Review, or its equivalent.

- **Final Design Load Cycle.** This loads analysis generally is completed in time so that any required corrective action can be implemented by making only drawing changes. The analytical model of the spacecraft is based upon a comprehensive structural analysis of the spacecraft design that has incorporated all design modifications resulting from both the previous load cycle and any basic program concept changes approved at the Preliminary Design Review. Typically, the Final Design Load Cycle results, in conjunction with other applicable structural design requirements, form the basis for the spacecraft Structural Qualification Test requirements. Prudent conservatism in the test loads is advisable since final verification of the adequacy of the test loads will not be achieved until the completion of the Verification Load Cycle, which occurs late in the program and after the structure has already been manufactured. The Final Design Load Cycle should be completed by the time of the Critical Design Review, or its equivalent.

- **Verification Load Cycle.** The loads from this cycle of analysis are intended as a final check of flightworthiness in that they form the basis for commitment to flight. For this analysis cycle, the assumptions inherent in complex dynamic modeling must be verified experimentally. This requires that dynamically complex components, such as the spacecraft, upper stage, fairing, etc., must be mode survey test verified. It is acceptable, and in some circumstances preferable, that the measured modes be used directly in the dynamic model. This is particularly true for the spacecraft. Another critical aspect of the Verification Load Cycle is the requirement that all loads analyses be verified by independent analyses. This includes independent validation and verification of analysis methodologies, models, forcing functions, and response calculations. The Verification Load Cycle and the Structural Qualification Test of the spacecraft must be completed prior to first flight.

The loads analysis program, as outlined, requires comprehensive analyses as well as careful planning and scheduling to assure orderly spacecraft structural design evolution. Experience has shown that it is well suited to the acquisition of launch and flight loads information for design and test purposes in a manner consistent with program milestones.

It should be remembered, however, that a single successful flight of a vehicle, because of normal flight-to-flight dispersions, does not provide proof of design adequacy. Thus, for those programs involving a sequence of launches, launch vehicle and spacecraft structural responses and forcing functions should be measured during flight. Loads analyses, using the Verification Load Cycle models, should be performed for the specific conditions of the flight for comparison with the measured flight dynamic responses. Any significant discrepancies between measured and predicted results should be resolved prior to succeeding flights.

5. Criteria for Independent Loads Analyses

It is important that the loads contractor's complex calculations be independently verified and validated to ensure that the final loads, which determine flightworthiness, are technically correct and error free. This requirement is satisfied, ideally, by independent analyses that meet the following conditions:

- **"Independently certified" mode survey test results are employed in the derivation of the spacecraft dynamic model as well as the dynamically complex launch vehicle components such as the upper stage and fairing.** Repetition of these tests to develop "independent" models is not necessary provided the independent organization that validates the launch vehicle models and the independent organization that validates the spacecraft model concur in the test planning and execution, and can certify the authenticity and accuracy of the results. In addition, every reasonable attempt should be made to satisfy the success criteria for the mode survey test and the subsequent analytical model to measured modes comparison specified below. Mode survey tests of launch vehicle components need to be performed once, and subsequent minor configuration changes, as well as propellant loading conditions, can be accounted for analytically, provided they are independently verified and validated.

Mode Survey Test Success Criteria:
All modes within the frequency range of interest (typically up to 70 Hz) must be identified and measured. In addition, the first two lateral modes in each of two planes, the first axial mode, and the first torsion mode, must be measured irrespective of their frequencies. The quality of the measured modes must be judged by computing the mass-weighted orthogonality of the modes. As a goal, the off-diagonal terms of the unit normalized generalized mass matrix should be equal to or less than 0.10. Satisfying this goal will not only increase confidence in the measured mode shapes, but also increase confidence in the dynamic model mass matrix.

Analytical to Measured Mode Comparison Criteria:
As a goal, the analytical model frequencies should be within three percent of the measured values, and the cross-orthogonality between the analytical and measured modes, each set normalized to yield a unit generalized mass matrix, should yield values equal to or greater than 0.95 on the diagonal, and equal to or less than 0.10 on the off-diagonal of the cross-orthogonality matrix. Any modeling adjustments/changes made to achieve the above-stated criteria must be consistent with the actual hardware and its drawings.

- **Independently verified and validated mass properties are used.** The mass distributions must be described in a fashion compatible with the structural dynamic models. The data presented in the contractors' detailed mass properties reports and weight statements should be assembled into a mass matrix consistent with the other properties of the structural dynamic model. Sufficient confidence in this database can be achieved by a review of the contractors' techniques for calculation and measurement of mass properties, together with spot checks and comparisons between calculated and measured results. The actual reassembly of the data into the mass matrix should be independently verified. Note that satisfying the orthogonality check described above increases confidence in not only the empirical modes, but also in the analytical mass matrix.

- **Independently verified and validated spacecraft model is used.** The results of the first two items described immediately above form the basis of the verification and validation.

- **Independently verified and validated load transformation matrices are used.** The stiffness and mass properties used to formulate these transformation matrices must be derived from models that have been adjusted per the above described procedures. In addition to using mode survey test data, static test data should also be considered.

- **Independently verified and validated launch vehicle models and forcing functions are used.** Models that are not primarily verified and validated by mode survey test data that satisfy the above stated requirements must be independently developed. Engine ground firing and wind tunnel data, and previous flight data should be independently analyzed as part of the forcing function verification and validation effort.

- **Independently verified and validated loads analysis methodologies are used.** This requires that the methodologies be developed independently from fundamental principles. In addition, the numerical implementation must be independent.

- **For all critical events, loads are determined by independent analysis.** Consideration should be given to the following flight conditions: liftoff and liftoff abort, atmospheric flight [transonic (Max Buffet), and maximum dynamic pressure (Max-q) times of flight as a minimum], engine shutdowns and ignitions, and separation and staging events.

- **Differences between the loads contractor's loads analyses and the independent analyses are resolved.** Results should be compared at appropriate and predetermined milestones so that differences that may arise can be reconciled with a minimum of re-analysis. Until differences are reconciled, an envelope of the two analyses shall be used, provided the cause of the differences is understood.

6. Management Procedures for Independent Loads Analyses

The requirement for an independent loads analysis should be identified as an element early in overall planning to assure the availability of adequate funding for this effort. Acknowledgment of the necessary services of all contractors in support of this work should be made in each contractor's Statement of Work (SOW) and, where appropriate, the Contract Data Requirements List (CDRL). In addition, suitable clauses in contracts are needed to assure cooperation among contractors in their joint performance of the tasks described herein.

The execution of the primary loads analysis involves exchanges of comprehensive data packages among several contractors. Experience indicates that the efficient and timely transmittal of such data requires careful coordination between the involved parties. It is important to ensure at an early date that each participant's tasks are accurately defined and realistically scheduled so that the various load cycles are completed in accordance with the program milestones indicated above. A Loads Working Group, chaired by the Air Force and comprising all contractor and independent technical representatives, should be established to ensure proper coordination and provide a forum for the resolution of problems. All data transmittal passing through the Loads Working Group should be subject to Air Force review and approval, including validation and verification. The independent loads analysis contractor(s) should become a member of the Loads Working Group no later than the conclusion of the Preliminary Design Review of the spacecraft, and should be provided copies of all prior data exchanges to allow for early familiarization with the characteristics of the configuration.

Special provisions are necessary to allow for participation of independent organizations in the planning and execution of the mode survey tests, including test article configuration, excitation methods, instrumentation characteristics and installation, data handling procedures, access to the test site to witness its performance, and accessibility to the test data as it is developed. The objective of this participation is to provide a means of coordinating accommodations that will allow concurrence in the adequacy of these procedures.

In order to facilitate the independent validation and verification of the mass matrices, provision should be made to assure the independent organizations' accessibility to the database that underlies the detailed mass properties report and weight statement for the launch vehicle and the spacecraft.

It is essential that the independent loads analysis be completed, and significant differences, if any, with the results of the primary Verification Load Cycle analyses resolved prior to first flight of the spacecraft.

7. Data Requirements for Independent Loads Analyses

The independent loads analysis contractor(s), if different than the organization validating and verifying the load cycle ingredients, should be provided with validated launch vehicle models, forcing functions, analysis methodologies, and a validated spacecraft model. These data should be sufficiently detailed to permit the construction of dynamic models of the flight configuration appropriate to each flight event to be considered, and to perform independent loads analyses. A widely used and efficient model transmittal format is described in Reference 5.

The organization responsible for validation and verification of the spacecraft model should be provided the structural drawings of the system, mass property reports, static and mode survey test data, and the bulk data deck for the spacecraft finite element model. In addition, the contractor-developed structural dynamic model and load transformation matrices should also be provided. These data requirements can be reduced if the contractor can show good agreement between the mode survey test results and the analytical model, or the measured modes are used directly in the structural dynamic model.

The organization responsible for verification and validation of the launch vehicle models, forcing functions, and analysis methodologies should be provided the structural drawings of the system, mass property reports, static and mode survey test data, and the bulk data decks for the vehicle finite element models. The contractor-developed structural dynamic model and load transformation matrices should be provided. In addition, wind tunnel data (e.g., aerodynamic, buffet), engine thrust data from flight and ground tests, autopilot description, and flight data for similar-configuration vehicles should also be provided. Although the analysis methodology needs to be derived independently from fundamental principles, the launch vehicle contractor should provide a description of its methodology to help the reconciliation of differences process. Once validated and verified, the launch vehicle contractor can provide, with Air Force endorsement, these data to independent loads analysis organizations.

8. Program-Peculiar Considerations

The discussion above deals with the most general class of loads analysis procedures. The present section describes the options available to Program Directors in prescribing independent analyses for their program.

Modern spacecraft are typically designed for minimized structural weight. Spacecraft that are designed for high structural weight efficiency are clearly those that require the greatest depth of analysis and for which there is no alternative to a complete independent loads validation in accordance with the precepts described above. Spacecraft designs are conceivable, however, in which structural weight efficiency is sacrificed to achieve other program objectives, with the result that the structure is overdesigned from the strength standpoint. In these instances, the depth of independent loads analysis may justifiably be reduced since confidence in the structure's ability to sustain launch and flight loads without failure is correspondingly increased. Under these circumstances, a range of options is available to the Program Director within the intent of this document:

- Perform a complete independent loads validation and verification for all critical flight events.

- Perform independent loads validation and verification only for the most critical events. Review for adequacy the data, procedures, and results of the Verification Load Cycle performed by the loads contractor for all other flight events.

- Review for adequacy all the data, procedures, and results of the Verification Load Cycle performed by the loads contractor.

In all circumstances, the participation by an independent agency in the planning and execution of the mode survey tests is considered essential.

In a mature program that involves a number of launches, the design of the spacecraft may be subject to modifications associated with "block changes." The kinds of modifications which have significant loads implications cannot be specified on an a priori basis, but typically they include all changes in the stiffness of primary structure, weight changes associated with the addition, removal, or relocation of significant subsystems, and changes in the stiffness of mounting structure. In all cases of block changes, the usual procedures for loads development and independent validation should be carried out.

For all programs, the Program Director's choice of depth and breadth of independent analyses is a decision based on a tradeoff of cost versus risk. However, the selection of any course of action other than the first option should be specifically called to the attention of the Commander for approval, at which time the rationale for the decision should be presented. Factors such as a spacecraft whose design is governed by stiffness considerations and is, therefore, not strength-critical, or one in which there has been deliberate imposition of unusually conservative structural design criteria, are considerations in the legitimate selection of one of the less-demanding options.

9. References

1) Fleming, E. R., "Spacecraft and Launch Vehicle Loads," Vol. I, Chapter 6, *Flight Vehicle Materials, Structures, and Dynamics*, American Society of Mechanical Engineers, March 1991.

2) Kabe, A. M., "Design and Verification of Launch and Space Vehicle Structures," AIAA 98-1718, presented at the 39th AIAA/ASME/ASCE/AHS/ASC Structure, Structural Dynamics, and Materials Conference, Long Beach, California, 1998.

3) Department of the Air Force, Headquarters Space and Missile Systems Organization, "Independent Structural Loads Analysis of Integrated Payload and Launch Vehicle Systems," SAMSO Regulation 550-5, Commander's Policy, 18 May 1979.

4) Department of the Air Force, Headquarters Space and Missile Systems Organization, "Independent Structural Loads Analysis of Integrated Payload and Launch Vehicle Systems," SAMSO Pamphlet 800-5, Acquisition Management, 15 February 1975.

5) Anderson, J. E., "A Generalized Coordinate Dynamic Model Data Format," Aerospace Technical Operating Report No. TOR-0078(3451-04)-1, 1 October 1977.

SMC Standard Improvement Proposal

INSTRUCTIONS

1. Complete blocks 1 through 7. All blocks must be completed.
2. Send to the Preparing Activity specified in block 8.

NOTE: Do not be used to request copies of documents, or to request waivers, or clarification of requirements on current contracts. Comments submitted on this form do not constitute or imply authorization to waive any portion of the referenced document(s) or to amend contractual requirements. Comments submitted on this form do not constitute a commitment by the Preparing Activity to implement the suggestion; the Preparing Authority will coordinate a review of the comment and provide disposition to the comment submitter specified in Block 6.

SMC STANDARD CHANGE RECOMMENDATION:	**1. Document Number**	**2. Document Date**
3. Document Title		

4. Nature of Change
(Identify paragraph number; include proposed revision language and supporting data. Attach extra sheets as needed.)

5. Reason for Recommendation

6. Submitter Information

a. Name	**b. Organization**
c. Address	**d. Telephone**
e. E-mail address	**7. Date Submitted**

8. Preparing Activity

Space and Missile Systems Center
AIR FORCE SPACE COMMAND
483 N. Aviation Blvd.
El Segundo, CA 91245
Attention: SMC/EAE