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Critical Clearances in Space Vehicles

October 31, 2008

Prepared by

Brian W. Gore
Mechanical Systems Department,
Structural Mechanics Subdivision

Prepared for

Senior Vice President, Engineering and Technology Group

Authorized by: Systems Planning and Engineering

APPROVED FOR PUBLIC RELEASE

THE AEROSPACE CORPORATION
EL SEGUNDO, CALIFORNIA

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Approved by:

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National Systems Group

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Abstract

Insufficient attention to critical clearances in space and launch vehicle systems has led to repeated instances of degraded performance and failures. Critical clearance related problems have also occurred in ground tests, causing cost impacts and schedule delays. As a result, a team of subject matter experts from several National Security Space companies was formed to develop a framework for improving the critical clearance process across the industry.

A review by the team of ground and flight incidents involving deployments revealed that one of the most prevalent root causes of deployment incidents was insufficient critical clearances. The team concluded that improvements should be made to Critical Clearance (CC) related processes to significantly improve ground testing and mission success rates.

A basic top-level plan and a detailed process map to support that plan have been developed and are explained in this paper. The Critical Clearance process applies to clearances at an assembly level above the MMA (Moving Mechanical Assembly) or unit level of assembly and not internal to the MMA or unit level. It is believed that strict adherence to the proposed critical clearance plan and process can greatly reduce the frequency of failures due to Critical Clearance losses. This paper was presented to the Space Quality Improvement Council (SQIC) / government / aerospace industry in June, 2008, to potentially aid in further development of current standards such as AIAA S-114-2005 (Moving Mechanical Assemblies), AIAA S-110-2005 (Structures), and guides for Critical Clearances.

Acknowledgments

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1. Introduction

Subject matter experts from various National Security Space companies reviewed 164 ground and 24 on-orbit anomalous deployment incidents and their root causes. Table 1 summarizes this study by showing the number of anomalies associated with various root cause "categories" shown. For the interested reader, Appendix A describes all the root cause "categories." There was some overlap between on-orbit causes, i.e., some anomalies had more than one cause, which is why the total is less than the sum of the individual categories. The table clearly shows that insufficient critical clearances caused the most ground test anomalies, and contributed on par with other causes to on-orbit anomalies. The purpose of this paper, under the auspices of the SQIC, is to assist in further focusing attention on critical clearances processes, with the goal of reducing the number of critical clearance related anomalies in the future.

Table 1. Test and Mission Anomaly Data

		Cause Categories				
Anomalies	**Total # Deployment Anomalies**	**Design mechanism**	**TLYF Exceptions**	**Offloading/ GSE**	**Critical Clearances (includes instrumentation)**	**Workmanship**
Ground	164	26	2	42	77	17
Percent	(100%)	(16%)	(1%)	(26%)	(47%)	(10%)
On-Orbit	24	17	10	1	10	6

Note: anomalies fit into one or more cause categories

This paper first provides definitions and categories for critical clearances and then provides a recommended top level plan and process flow to better address critical clearances. A flow chart is provided for the critical clearances process overview and each step is discussed later in detail to assist in understanding the flow chart. Specific anomaly examples are cited where appropriate.

Critical clearance related problems can be attributed to design, workmanship, and/or test (verification) deficiencies. The recently released AIAA standard on Moving Mechanical Assemblies (AIAA-S-114-2005) addressed many design and test issues, and test-like-you-fly exceptions are the subject of a separate broader effort currently underway. Therefore, it was felt that focusing on the critical clearance assessment process area would provide the greatest potential benefit.

The technical team, whose members are listed in Table 2, studied the current best practices to establish Critical Clearance processes at the appropriate level of integration. The recommendations in this paper are not intended to constrain contractors, as methodologies are constantly evolving, but to produce guidelines that can remain stable and relevant in the face of changing needs.

Table 2. Critical Clearance Team Membership

Company	Role	Name	Phone	e-mail
Boeing	Chair	Art Zapf	310-416-8030	arthur.zapf@boeing.com
	Facilitator	Michelle Matsuoka	562-797-1494	michelle.matsuoka@boeing.com
Aerospace	Co-Chair	Brian Gore	310-336-7253	brian.w.gore@aero.org
	Member	Leon Gurevich	310-336-1268	leon.gurevich@aero.org
LMSSC	Member	Mike Pollard	303-977-6426	mike.p.pollard@lmco.com
Ball Aerospace	Member	Bill Schade	303-939-7034	wschade@ball.com
NGST	Member	Brian Norden	310-813-8650	brian.norden@ngc.com

Sponsors: National Security Space Mission Assurance Workshop; The Aerospace Corporation, Ball Aerospace, Boeing, Lockheed Martin, Northrop Grumman

2. Definitions

Critical Clearance (CC): A clearance between two space and/or launch vehicle components and/or GSE is deemed "critical" if the reduction of the clearance at any time results in mission or test degradation, anomaly, or failure. For the scope of this document, these clearances of interest are at an assembly level above the MMA or unit level of assembly and not internal to the MMA or unit.

Critical Clearance Coordinator (CCC): Engineer or organization supporting the program with overall responsibility of execution of the critical clearance process on that program. Overall responsibility of the process should be owned and coordinated by the company's mechanical and/or systems engineering organization.

Range of Motion (ROM): The complete angular or linear space through which a component (such as a motorized gimbal or spring-driven deployment mechanism) moves once or more during a mission.

Loss of Clearance (LOC): A reduction in clearance.

LOC Analysis: The analysis is an evaluation of all contributions to LOC to determine the minimum predicted distance between bodies.

Moving Mechanical Assembly (MMA): A device that controls the movement of a deployable or other movable system of a space or launch vehicle, including, but not limited to: deployment mechanisms, sensor mechanisms, pointing mechanisms, drive mechanisms, de-spin mechanisms, separation mechanisms, momentum and reaction wheels, control-moment gyros, gimbals, and other mechanisms required to perform specific functions.

Ground Support Equipment – Mechanical (GSE): Equipment or instrumentation used in assembly, integration and test operations that can have an impact on clearances or ground test or flight Critical Clearances and deployments, such as 1-G offload attachment hardware, handling brackets, and test harnesses.

3. Clearance Categories

Moving/ Dynamic Clearance: Clearance between two components where one is moving relative to the other component. These include solar array deployment, antenna deployment, gimbal rotation.

Anomaly Example: A moving clearance failure can result in a deployment failure such as the 1991 documented on-orbit anomaly of the Anik E2 C-Band antenna[1]. The antenna failed to deploy when the launch locks were released. The cause was determined to be blanket interference. Significant work by engineers freed the antenna using thermal soaking, higher spin rates, and space vehicle nutation.[1]

Non-moving/ Static Clearance: Clearance between two fixed/stowed space vehicle components where LOC occurs from launch environments, thermal distortion, or other factors. These include stowed solar array to radiator, and secondary structure to antenna assembly clearances.

Anomaly Example: On the NOAA-B spacecraft in 1994, a protruding screw disabled a battery charger by penetrating the cable insulation and creating an electrical short.[1]

Launch Vehicle Interface (LVI) Clearance: Clearances between a space vehicle component and the launch vehicle are defined by the launch vehicle static and dynamic envelopes. These clearances are often reduced during vibration at the space vehicle's minimum fundamental frequency, or during staging/separation. These include payload clearances to fairing, and separation clearances such as upper stage nozzles to lower stage hardware.

Transportation and Handling Clearance: Clearance between a space or launch vehicle component and its shipping container, environmental test chamber, or other entity involved in the non-functional movement of the item. These include shipping containers, ingress/egress to/from thermal chambers, and integration of space or launch vehicle modules.

GSE Clearance: Clearance between a space or launch vehicle component and any specific piece of hardware used for the assembly, integration and/or test of the vehicle. These include the GSE required to offload deployable elements against the effects of gravity, and lift system for space vehicle movement.

Anomaly Example: TVSat1 had an on-orbit failure in 1987, where one solar panel failed to deploy because a hold down clip had not been removed prior to flight.[1.]

Non-Contacting Clearances: Clearances to stay out zones, such as sensor, thermal, and antenna fields of view / fields of regard, magnetic keep-out zones, and thruster plume envelopes.

4. Top Level Critical Clearance Plan

A top level plan is essential for establishing a critical clearance process that will have a successful impact on the space or launch vehicle. Rigor and adherence to process will produce positive results. It is important to understand that the process, and commitment to the intent of the process, must start early in the program flow, and must be supported throughout the corporate hierarchy, or its value will be greatly reduced.

There are three primary phases of the Critical Clearance Process:

1. Establish Critical Clearance Criteria
2. Establish an Execution Plan
3. Execute the Critical Clearance Process

One of the most effective approaches involves identification of a focal point on each program with overall accountability for the execution of the process. The CCC (Critical Clearance Coordinator), for example, coordinates between design organizations to identify, track, analyze, and verify critical clearances to ensure success.

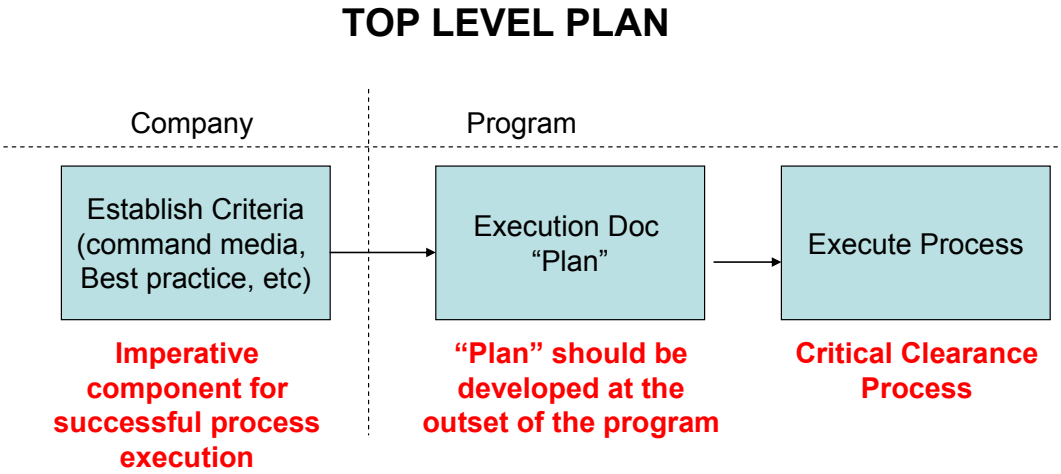

Figure 1. Top level process.

It is imperative that the critical clearance criteria be established by each company through their command media or engineering best practices for this process to be effective. The criteria should include design standards or guidelines that delineate clearance thresholds based on design maturity and/or critically for the critical clearance categories listed above, as determined by the company. Beyond this initial step, this paper addresses the process in the following pages to provide a breakdown of the recommended steps for the execution of the clearance process. Each process step is explained in detail to provide rationale for movement through the process boxes.

As noted, this process must be driven and controlled by a CCC who is responsible for the execution of the critical clearance process including coordination across the engineering, manufacturing, and test disciplines. The overall process should include oversight, traceability and analysis at the system level. The CCC is also responsible for verification. To garner the greatest chance of a complete, thorough, and successful process, the CCC should be identified early in the program, and retained through all program phases.

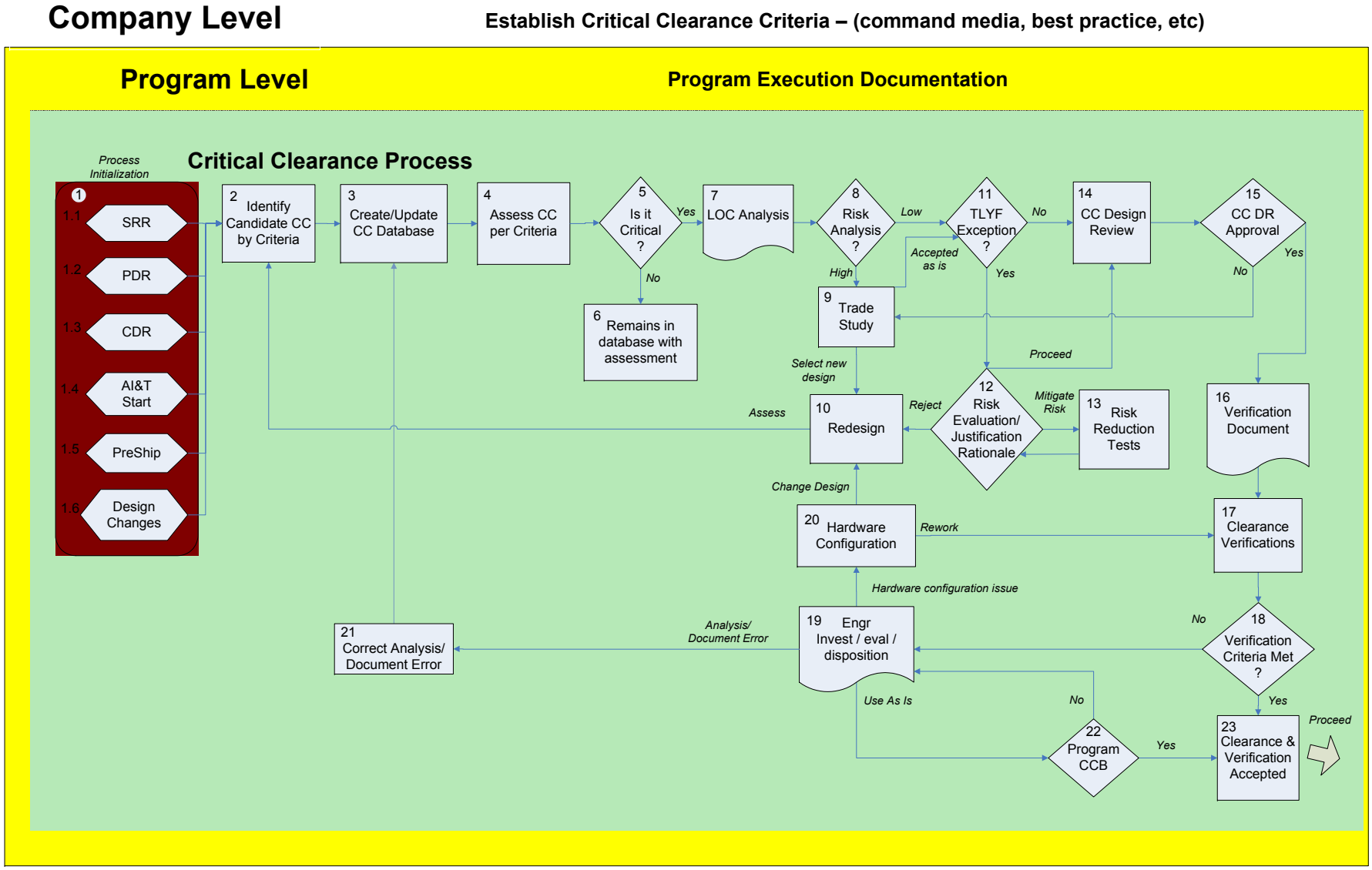

Figure 2. Critical clearance process map.

5. Critical Clearance Criteria

The critical clearance process is based upon a necessity to identify, analyze, and verify clearances to prevent mission failures or degradation as a result of contact during the mission. Whether it is prevention of contact between components during the launch vibration environment or adequate clearances for successful deployment of antennas and solar arrays, a threshold of sensitivity must be established to guide the execution process. Design clearance guidelines and minimum acceptable clearance criteria – which trigger rigorous loss of clearance analysis – are essential to guide the verification process and provide confidence for flight.

It is recommended that companies establish clear critical clearance criteria that take into consideration:

a. The three basic clearance categories (at a minimum): Static, Dynamic, and Launch Vehicle Interface
b. Minimum final design clearances, below which would require LOC analysis, based on design maturity
c. Worst case mission acceptable clearances
d. LOC assessment methods for moving, static, and LVI clearances (at a minimum)
e. Compliant structures, including blankets, thermal shields, harnesses, sunshields, etc, and any other items with potentially large uncertainties in position.
f. Effects of ascent venting, 1G release, electrostatic forces, etc on blankets.
g. Relative motion between components, over full ROM, and taking CONOPS into account
h. Ability to verify clearances prior to launch, either by test or inspection.

6. Execution of the Process

The role of the program office is to provide documentation and support for the execution of the critical clearance process via company command media. A critical clearance execution plan should be put in place early in the program, which appoints an engineer to the role of the "Critical Clearance Coordinator." The CCC will provide all coordination with the design team and verification teams through completion of the program or encapsulation of the space vehicle. As can be seen in the detailed steps below, the process is rigorous, continuous, and cyclical – it is NOT a one-time effort. The clearance analysis and data assessment is living process all the way through the verification steps. The CCC carries a heavy responsibility, and requires the support and authority of the program office for proper execution. Thus the CCC's early involvement in the program is critical, starting no later than concept of design (COD) and continuing through launch.

7. Process Steps Description

7.1 Process Initialization

The critical clearance process is a continuous endeavor with a cyclic nature. Although the desire for any program is to have a single, one-pass process, there are always design changes, late maturity, late engineering changes, and potential late contract requirement adjustments. Thus the critical clearance process must adapt to the flexibility of program schedules to stay current with designs and have a realistic opportunity to root out critical issues and preserve the quality of the intended product. There are five major cycles for the critical clearance process, and potentially more depending on the life of the program, and the program should start the process early enough to support these milestones:

i. As part of the system requirements review (SRR)
ii. As part of the preliminary design review (PDR)
iii. As part of the critical design review (CDR)
iv. At the start of assembly, integration and test (AI&T)
v. Prior to the pre-ship review (PSR)

A complete review of the critical clearance database should be performed for each of these major milestones. Establishing and maintaining a process to screen all Critical Clearances related engineering releases and changes via the CCC are essential for clearance impact assessment. (If there is doubt that the engineering change is CC related, the CCC should be consulted). This is especially true for late changes.

7.1.1 SRR - System Requirements Review

Initiation of the CC process may start before or during the SRR period. Review and confirmation of the program CC plan's execution documentation should occur by the SRR, as well as designation of the CCC. At SRR, all known candidate critical clearances should be identified and tracked in the clearance database and CCs identified. CCs below the CC design thresholds, deemed appropriate for this phase, should be identified, and mitigation plans should be made to increase those clearances above their CC design threshold, unless otherwise deemed acceptable. .

7.1.2 PDR – Preliminary Design Review

At PDR, the basic design exists under the critical clearance criteria and should be screened through the critical clearance process for risk. At this stage of the process, clearances are tracked and reviewed for potential improvements. The CCC collects and tracks these clearances through the process as the design matures. This improvement cycle primarily flows through step 9 and 10, and cycles until the CDR time period. Early consideration for verification plans should be considered, to address the TLYF exception in step 11, and to ultimately allow for completion of the process to step 23.

7.1.3 CDR – Critical Design Review – program

As the program CDR approaches, all clearances meeting the criteria standards should be well known. Each should have already been vetted through risk assessments and loss of clearance analyses by the CCC and all the design and support organizations. Coincident with the CDR, an independent review should be held by the CCC to ensure that all identified critical clearances are acceptable to the program and the company to take forward into the final design. This process primarily cycles through steps 1 to 15, but also should show a clear path to completion to step 23. Approval of the review and closure of all actions is required to proceed to the next step of creating the verification documentation.

7.1.4 AI&T – Assembly, Integration & Test

At the beginning of AI&T, the program must have completed all actions from the critical clearance design review and released the critical clearance verification documentation so it is ready for use. Throughout this juncture, it is very important to know that all late engineering (post-CDR) has been reviewed for impact to clearances and that the analysis and verification documents are up to date, throughout the normal assembly and integration process. The CCC should coordinate with the verification team prior to proceeding with the verification steps.

7.1.5 Pre-Ship

Prior to shipment at the end of AI&T, the CCC should verify that the verification documentation is current and all late changes or adjustments through AI&T have been incorporated in the LOC analysis, and that the process is completed for all CCs, through to step 23. All outstanding non-conformances should have been resolved. The CCC must be able to justify the existing design with the completed verification document at this time.

7.1.6 Late Changes

As stated above, any late changes (whatever the source) are an important consideration in the process. The hardware must be inspected to the correct design requirements and expected clearance predictions. Any change can be potentially significant. For that reason, this process map re-iterates the process for design changes that may impact CCs. (If in doubt, the CCC should be consulted). And, of course, it is imperative that there is a focal point (CCC) to ensure that this is completed, even at late stages.

7.2 Identify Candidate Critical Clearances per Criteria

During the design/redesign process, space vehicle clearances are screened against the company established criteria. All clearances below the thresholds are flagged and coordinated with the CCC for future reference, as are those clearances that might be suspect to become CCs. A picture or 3D screen shot and the nominal clearance should be provided for inclusion in the critical clearance database. This process can be for new additions or updates to existing clearances depending on the maturity of the design.

7.3 Create / Update Critical Clearance Database

The CCC creates and maintains the critical clearance database. All design clearances flagged are logged with the nominal clearance for further evaluation. This includes late changes that may increase, decrease, or create a new clearance. Any unique attribute or constraint should be noted for further consideration, such as when the clearance occurs and what factors are involved.

7.4 Assess Critical Clearance

The CCC works with the applicable cognizant hardware engineer (CHE) to assess the clearance, as to whether it should be identified as a CC. Depending on the program size, it may be appropriate to establish IPT CCCs and a CC working group. This is based on the established CC criteria, but can also include other factors. For instance, while risk is addressed later, it too can influence this decision based on the probability and consequence of contact. So this step may be based upon engineering judgment beyond the CC criteria and thus requires an experienced engineer working with the CHE to make an appropriate assessment. A static clearance with no consequence is not deemed critical, and is relegated to remain in the database with its ranking. Static clearances with sufficient consequences, and all moving clearances meeting the criteria, are deemed critical, and should be identified as such and processed further through loss of clearance analysis for a more precise understanding of the actual mission clearance.

7.5 Critical Decision

As stated in step 4, a non-critical clearance remains captured in the database. A clearance evaluated and identified as critical moves forward to the LOC Analysis in step 7.

7.6 Remains in Database with Assessment

The CCC logs the rated 'non-critical' clearance in the critical clearance database with the basis for that rating. This serves as a reference for future evaluation, and notation that it has been screened and deemed non-critical. Should a subsequent design change occur (as in Step 1) that might affect this clearance, a re-assessment should be performed for criticality.

7.7 LOC Analysis

It is expected that companies will develop loss of clearance assessment tools for this process step. There are many contributors to loss of clearance. LOC analyses, beginning with nominal dimensions, should account for worst case mission clearances to include, but not be limited to, the following contributors: manufacturing, thermal distortion, dynamic (during all mission phases) ground transportation, dry out, worse case thermal blanket configuration, 1-G effects, GSE and pressurization. The output of the LOC analysis should include the worst case mission clearance predict with a worst case associated ground measurement verification predict.

7.7.1 Thresholds

The LOC analysis should compare worst case mission clearances against company sensitivity thresholds. Multiple thresholds may be established to account for criticality, design maturity of the subsystem, and the level of measurement uncertainty that exists in the hardware (i.e., is it drawn, built, installed, etc.). Application of these thresholds may change throughout the life of the program.

7.7.2 LOC Assessment

Analysis should include all contributors to loss of clearance between critical components and include model uncertainty factors. Using the analysis tool, LOC should be considered for, but not limited to, the following contributors:

7.7.2.1 Manufacturing and Assembly Tolerances

Analysis should include all contributors of size and positional tolerance. These include, but are not limited to:

a) material thickness,
b) flatness,
c) angularity,
d) run out,
e) alignment allocation,
f) bolt/hole clearance (to account for potential launch shifts),
g) shim tolerances, etc.

It is recommended that a statistical approach may be used.

7.7.2.2 Thermal Distortion

Considerations for thermal distortion effects on hardware can be critical during mission operations. There are two primary conditions that should be assessed, coefficient of thermal expansion (CTE) differences and thermal gradients / transients.

7.7.2.3 Dynamic Loss of Clearance

Dynamic loss of clearance is one of the most important considerations for loss of clearance and must be considered for several phases of the space vehicle mission. Engineering should evaluate LOC for each case through analysis such as FEMs. Dynamic LOC can come from one or more of the following sources:

7.7.2.3.1 Launch Dynamics.

LOC from launch vibration can have tremendous impact on the clearances between critical space/launch vehicle elements. Failure to properly assess this clearance loss can result in complete or partial mission failure.

7.7.2.3.2 Transportation

LOC of clearances for all space/launch vehicle components should be considered for ground handling and transportation activities. This is typically bounded by truck transportation or airplane landing loads. Clearance can be lost between space vehicle components or between the space/launch vehicle and the shipping container.

7.7.2.3.3 Launch Vehicle Separation

LOC from launch vehicle events covers two areas. The first area is the fairing separation clearance to the space vehicle, and the second area is the separation from the launch vehicle adapter. Aside from clearance between space and launch vehicle components, the tip off angle restriction, which is usually contained with the launch vehicle ICD, also needs to be considered; this is normally done with multi-body dynamic simulations.

7.7.2.3.4 On-Orbit Dynamics

LOC can occur during several on-orbit operations. The frequency of a fully deployed space vehicle is somewhat softer with deployed elements. While displacements are usually small, considerations should be taken for critical areas. LOC can occur from slewing, orbit adjustment, thruster firings, and other space vehicle maneuvers.

7.7.2.3.5 Deployments

The primary objective of critical clearances is to ensure that the space vehicle deployments can occur without impediment. In addition to other LOC contributors, it is important to consider what, if any, dynamic effects during deployment can occur to reduce critical clearances. These can include instantaneous strain relief upon release from launch locks, resonance vibrations from other space vehicle disturbances, changes in temperature/distortion, etc,

7.7.2.4 Dry Out

While seldom a contributor, dry out effects of composite structures should be assessed for LOC contributions. This is more likely seen in large composite structures where small clearances to rigid stable structures can produce concerns.

7.7.2.5 Soft Structure/Thermal Control Materials

Thermal blankets and multi-layer insulation (MLI) are some of the hardest materials to establish configurations and control. These materials are hard to locate repeatably, are very flexible, and deform easily from external effects. One of most difficult problems to assess is the final or worst configuration caused by the air venting during the ascent out of the atmosphere, commonly referred to as ‘billowing’. The resulting configurations can be somewhat different from the configurations during ground-based, zero-G simulation testing. The challenge is to understand worst case configurations and to account for them in the LOC analysis. Combined with other LOC contributors,

the results can be disastrous during mission operations. The CCC should assess all designs for the blanket configurations and their worst case conditions.

7.7.2.6 One-G effects

One of the challenges for LOC analyses is to determine expected clearances during AI&T operations and their corresponding worst case clearance during the mission. A key factor is the ground testing of hardware in 1-G for a zero-G space application. Deployable elements are often not designed to support their own weight on the ground. Depending on the type of deployable element, the method for offloading or negating gravity effects can be a challenge. Certain inaccuracies will be inherent due to stiffness or the inability to provide accurate offloading. Analysis predictions for these effects during test should be factored into the LOC analysis as well as uncertainty. Note that in some cases 1-G effects should also be considered for static clearance assessments/verification.

7.7.2.7 Pressurization

Expansion of pressure vessels should be considered for static clearances, when appropriate. Tanks expand when fully pressurized for the mission, but will occupy a smaller volume during ground clearance verification activities.

7.7.2.8 Harness

Typically wire harnesses, cabling, and cable ties/clamps are not considered hard structure, and their configurations and location can vary significantly. Harnesses are subject to damage when in close proximity to abrasive surfaces or sharp corners, thus their routing is important for assessment. All harnesses should be evaluated for position and tolerance. Lastly, harnesses can have an impact on deployments when routed across deployment hinge lines. These cases should be assessed for CC criticality in addition to the other concerns, and LOC addressed based on the motion they will experience. The CCC should assess all designs for harness configurations under their worst case conditions.

7.7.3 GSE Factors

Ground support equipment (GSE) has the potential to introduce additional CCs. GSE should be assessed to assure that ground verified clearances represent expected mission clearances. GSE configuration should be evaluated to ensure that no unacceptable artificial forces, deformations, or clearances are imposed on flight hardware. All variations between test and flight configuration should be accounted for in the loss of clearance analysis and/or verification.

7.7.4 CONOPS

Concept of operations should be considered as part of the CCs process. It may be necessary to establish multiple steps or sub-step verification steps to demonstrate the overall compliance. Off-nominal CONOPS scenarios should also be considered, resulting from off-nominal conditions, single failures, etc.

7.8 Risk Analysis

The mission clearance should be compared to 'minimum acceptable criteria' and evaluated for risk. A clearance believed to be well understood and meeting the criteria is a candidate for the verification document. A clearance below the criteria or one that has higher than desired residual risk should be considered for alternate design solutions in step 9.

7.9 Trade Studies

A clearance deemed unacceptable or high risk should be reviewed with a goal of a design modification for improved clearance. Alternate solutions should be traded for cost and schedule to reduce risk, and to provide a lower risk design. Outcomes of these studies can be a program decision to change designs or to retain the existing design with justification.

7.10 Redesign

If a redesign solution is selected, the approach should provide improved clearances or reduced risk, possibly through a more robust design approach with high repeatability. The new design must then be assessed for criticality once more, since one outcome of the redesign could be such an improved clearance that the probability portion of the assessment becomes remote and no longer satisfies the criticality filter.

7.11 Test Like You Fly (TLYF)

Once a clearance has been analyzed and determined that verification by inspection or test will be required, it will be necessary to determine how and during which build phase the verification should be performed. The goal is to verify all clearances early and as close to a flight like state as possible, at the earliest opportunity, and to repeat that verification if the hardware configuration is changed or adjusted during the AI&T activities. In cases where a clearance cannot be verified in the correct sequence, or will be unavoidably disturbed following verification as part of the integration process, the program identifies these as exceptions to "Test Like You Fly." These exceptions are evaluated in step 12 for acceptable risk.

7.12 TLYF Risk Evaluation/ Justification/Rationale

Justification for a TLYF exception should be supported by a risk assessment. If the risk is too high, the clearance should be rejected and reconsidered for redesign, or a test developed to mitigate/characterize the risk. The test results are evaluated and a justification with rationale is provided for consideration for acceptance in the design review, step 14. Unacceptable test results can still lead to a design change.

7.13 Risk Reduction Tests

High risk TLYF exception clearances can potentially be mitigated through adjunct testing. Mockup or engineering model hardware can be used to demonstrate high repeatability of installation or operation affecting a clearance that cannot be physically verified following final assembly.

7.14 Critical Clearance Design Review (CC DR)

The CCC should conduct a program design review with subject matter experts (SME). Reviews of clearances should be performed at each major cycle, SRR, PDR, CDR, pre-AI&T, and preship. For the late design or risk changes, each should be vetted through a senior review if significant change or impact is determined by the CCC or SME. The most significant review should coincide with the program CDR. Successful completion, including closure of actions of this review, is essential prior to proceeding to the verification phase. Note that all TLYF exceptions should be evaluated through these reviews as well.

7.15 CC DR (CC Design Review) Approval

While all final clearance assessments require review and concurrence, the majority of the clearance assessment work in a forward pass non-recurring effort is scrutinized during the CDR time period. Successful completion of a CC DR / CDR should include review board consensus and closure of all recorded action items.

7.16 Verification Document

Release of the critical clearance verification document should follow successful completion of the major CC DR (CDR time phase). Although this document is not released until after the CDR time phase, it may be created earlier and used to manage clearances. This document should contain depictions of the individual clearances along with the measurement/verification requirements. This document becomes a "living document," supporting the data collection and providing the final verification of critical clearance requirements. Clearance verification may be specified more than once during AI&T, such as pre- and post-environmental exposure operations. It should be noted that when design changes occur and are vetted for clearance concerns, the critical clearance analysis data base should be updated and flowed into the verification document. It is the CCC's responsibility to ensure that this document stays current with the engineering.

7.17 Clearance Verification

It is in this step that the critical clearances are verified by executing requirements of the verification document. Measurements/inspections are performed throughout the AI&T process to validate clearances. Where applicable, variations/changes in measurements between pre- and post-environmental exposure should be evaluated. The last measurements such as prior to hardware delivery and/or during flight final and launch site operations are extremely important to be complete, following final assembly and close-out. Measurement method and uncertainty should be accounted for in the verification process.

7.18 Criteria Met

All critical clearances should be evaluated against their verification criteria. CCs meeting the criteria constitute accepted clearances, based on accepted verification(s). All clearance verifications should require the CCC's approval. Any clearance failing the minimum verification predictions should be referred to non-conformance processing and engineering review. Non-compliances should be

processed via company non-conformance procedures according to step 19. The CCC should be part of this process.

7.19 Engineering Investigation/Evaluation/Disposition

All critical clearances failing to meet their criteria should be processed through normal company non-conformance processes. Engineering, including the CCC, should determine the cause of the non-conformance and the appropriate corrective action. If the non-conformance is minor, a "use as is" disposition may be appropriate assuming adequate margin. Acceptance through step 22, program Change Control Board (CCB) should provide sufficient scrutiny for the associated risk. Generally, a critical clearance non-conformance is a result of either a hardware configuration problem or a CC analysis error. If it is determined to be an analysis or document error, proceed with step 21. If it is determined to be hardware configuration, then the design must be reviewed per step 20.

7.20 Hardware Configuration

If hardware configuration is determined to be the cause, either a rework to print and re-verification may solve the problem, or a design change may be necessary. If reworked to print, such as a blanket redress, then return to step 17 for clearance re-verification. If the per-print hardware is non-compliant, then the design must be re-assessed.

7.21 Analysis/Document Error

If the LOC analysis is determined to be in error, then the process returns to step 3, updating the CC database, assessment, and analysis, and vetting through the process to obtain an acceptable outcome. Sources of error can be due to model errors, late changes, misunderstood configurations, blanket billowing assessment, or others.

7.22 Program CCB

A CC verification non-conformance that is deemed acceptable should be scrutinized and approved by the program CCB to ensure that the risk is acceptable. There may be cases where a clearance measurement fails a ground requirement by a small amount and sufficient mission margin exists to accept the risk. If the program CCB rejects the use-as-is recommendation, return to step 19 for further evaluation.

7.23 Clearance Accepted

This constitutes the end of the CC process, where all critical clearances have been verified and the space vehicle is ready to fly. The ultimate goal is that every item in the CC database has been verified or accepted for risk. The program may then proceed to the next appropriate step, with CCs resolved for each appropriate phase.

8. Conclusions

Studies of a sampling of test and flight performances indicated that insufficient attention to critical clearances in moving mechanical assemblies has led to repeated instances of degraded deployment performance or failures of satellite systems. The CC team's brief review of this industry data substantiated the clearance process recommendations, as presented herein. Benefits of this process can be realized by utilizing it and its intent, to the extent best appropriate for existing or future programs, commensurate with their desire for a lower risk solution.

It is recommended that critical clearance criteria be established by companies through their command media or engineering best practices for the process to be effective.

The Critical Clearance assessment process applies to programs at the subsystem level, that is, for the integrated assembly of sub-assemblies, such as a Moving Mechanical Assembly into its next higher level of assembly in a spacecraft.

The Critical Clearance process flow developed in this paper should be executed as many times throughout the program life cycle (for PDR, CDR, AI&T, preship, and design or hardware changes) as needed to meet the acceptance criteria for all CCs through each phase or cycle. This includes a complete review or assessment of all CCs and overall CC rechecks as the design matures, which should result in significantly improved probability of test and mission success.

The company designated process owner for Critical Clearances is an important element. This can be accomplished by establishing a Critical Clearance Coordinator who is responsible for the execution and verification of the critical clearance process, including coordination across the engineering, manufacturing, and test disciplines, to verify that all CCs are acceptable for test and mission success.

The CCC should be qualified to address the rigors and complexities related to the CC process, such as Test Like You Fly (TLYF) exceptions that may need additional evaluation to best address certain critical clearances. The CCC should also play a crucial role in challenging the design / review process to best address known higher risk CC items, such as for deployable elements, blankets, harnesses, compliant structures, etc.

9. Recommendations

Command media or an engineering best practice for a critical clearance process should be established by the respective company in order for the process to work.

Analysis tools should be developed by the company to ensure that the loss of clearance analysis is accurate and complete.

Implementation of a critical clearance process throughout the industry is recommended and can be affected by injection of pertinent references to this paper, or a derivative of it, for critical clearance process/verification. This paper may be referenced by contractual documents. Examples of specifications that may be reviewed for such an approach include, but may not be limited to the following.

- AIAA S-114-2005 (MMA Standard)
- AIAA S-110-2005 (Structures Standard)
- MIL-STD-1540E, SMC-S-016, or equivalent (Test Requirements for Launch, Upper-Stage, and Space Vehicles)
- MIL-HDBK-340 (Application guidelines for MIL-STD-1540 testing requirements)

References

1. Harland, David M., and Ralph D. Lorenz. *Space Systems Failures, Disasters and Rescues of Satellites, Rockets, and Space Probes*. 2005. UK: Praxis Publishing. pgs. 296, 300, and 316.

Appendix A. Root Cause Categories

The SMEs on this team reviewed ground and on-orbit deployment anomalies for root causes. The anomalies were categorized into cause categories where some overlap occurred. In other words, some of the anomalies had more than one cause which in reality could be serial: i.e., a design error that led to a clearance problem. The following are descriptions of the different categories used for this tally.

Design/Mechanism: This category collected anomalies where the deployment failure was a result of either a design error or mechanismal function.

TLYF: This category collected anomalies that resulted in deployment failures because the configuration in which it was tested was not the same as the flight hardware.

Offloading/GSE: This category collected anomalies caused by ground test hardware or methodologies that did not represent the flight deployment sequence or configuration. These include GSE design problems and offloader setup errors.

Critical Clearances: This cause category collected anomalies that resulted from a loss of clearance.

Workmanship: This category collected anomalies in which flight final workmanship was not rigorous and resulted in a failed deployment.

Appendix B. "Test Like You Fly" (TLYF)

There are multiple terms used today, most interchangeably, with regards to testing configurations. Test Like You Fly (TLYF) and Test As You Fly (TAYF) are two of the most common. The literal translation produces many questions. The TLYF topic team under this mission assurance workshop covers a wide range of issues including software, electrical, test validation and others. TAYF can be interpreted as testing "as (while) you are flying", although it is normally interpreted "as you will fly". On the other hand, "like" is defined as "similar to" or resembling" in the dictionary. This white paper makes no distinction between the two. However, in the context of critical clearances, clearance verification performed during space vehicle flight final must be "exactly" as it will fly. "As" has been used for this description and "'like" can be used, but it is most important that it is understood relative to critical clearance verification that the hardware must be exactly the same, untouched from the last deployment verification test.