A HANDBOOK TO SUPPORT THE NASA POLICY TO LIMIT ORBITAL DEBRIS GENERATION - A PROGRESS REPORT

BY: ROBERT C. REYNOLDS*, JOSEPH P. LOFTUS+, DONALD J. KESSLER+, AND ROBERT W. WEINSTOCK**

*LOCKHEED ENGINEERING & SCIENCE COMPANY, +NASA JOHNSON SPACE CENTER/HOUSTON, TX.
**VITRO CORPORATION/ WASHINGTON D.C.

ABSTRACT

A Handbook is being developed to support the NASA policy to limit orbital debris generation. This Handbook establishes guidelines for limiting the generation of orbital debris, provides support for developing programs to help them establish conformance to these guidelines, and supports the assessment of effectiveness of debris mitigation procedures.

The Handbook covers five broad areas: debris released as a normal part of mission operations, debris generation by explosions, debris generation by collisions, post-mission disposal of space structures, and debris footprints on reentry. The Handbook is organized around guidelines for specific debris issues. These guidelines provide acceptable measures for limiting the generation of orbital debris; an evaluation methodology and parametric data is presented for each guideline along with supplemental software.

In this paper, the structure and contents of the Handbook will be reviewed. Projected activity leading to completion of the current project will also be discussed.

1.0 INTRODUCTION

United States policy requires that space activities be carried out so as to minimize orbital debris. The NASA implementation of this policy is the NASA Policy to Limit Orbital Debris Generation as stated in NASA Management Instruction (NMI) 1700.xx. The NMI states: "NASA's policy is to employ design and operations practices that limit the generation of orbital debris, consistent with mission requirements and cost-effectiveness." The NMI requires that each program or project conduct an assessment to demonstrate compliance with this policy. The NMI is currently being reviewed within NASA.

The debris assessment as specified in the NMI must address the potential for orbital debris generation during normal or abnormal mission operations, debris generation as the result of on-orbit collisions and the potential risk from atmospheric reentry. Release of operational debris such as lens covers, shrouds, and staging components are examples of debris generation during normal operation. On-orbit explosions are examples of debris generation during abnormal operation. Debris generation via collisions includes the immediate generation of debris generation by catastrophic collisions with large objects and the indirect creation of debris by abandoning structures at the end of mission life or by loss of control of spacecraft by design fault or impact with small debris, either of which could lead to later fragmentation by impact with large debris.

The Handbook is designed to allow the program manager to address debris issues during program development - early in the development cycle to identify and resolve potential problems when cost impacts will be minimal, and later when levels of risk and effective mitigation measures can be stated for specific program parameters. The Handbook provides guidelines, analysis methods, and software to assess debris generation and the potential for collision with existing orbital debris. In addition, the Handbook specifies the information that should be included in the assessment reports. Handbook software is provided to analyze special case situations or to perform analyses using the particular parameters for a specific program. This software runs on a 386/486 desktop computer and is designed to run interactively.

2.0 DISCUSSION

In response to the threat posed by the accumulation of orbital debris, NASA is implementing a policy to limit orbital debris generation consistent with mission requirements and cost effectiveness. This policy requires each program to conduct a formal assessment of its the potential to generate orbital debris. A Handbook to support implementation of the policy is being prepared by NASA to reduce the time and costs for performing such assessments and to assure consistent standards and criteria across projects. This work is being sponsored by the Office of Safety and Mission Quality (Code Q) at NASA Headquarters.

The threat of collision with orbital debris is an issue of growing concern as historically accepted practices and procedures allow manmade material, often potentially explosive material, to accumulate in orbit. In the past explosions have been the primary source of debris, and they can be expected to be so in the near future. However, assuming no increase in the number of launches per year, if spacecraft and upper stages continue to be left in orbit at the end of their mission, current models indicate that by the year 2040 collisions between large objects will become the major source of debris and lead to a large increase in the amount of debris that could damage or disable operating spacecraft. If the number of launches increases only slightly each year (by 5% of the number of 1990 launches), collisions between large objects in orbit should become a significant source of debris much sooner, by the year 2015 (Ref. 1).

Debris environment projections have shown the necessity for initiating mitigation measures (Ref. 2-4) and current work at NASA/JSC is demonstrating the effectiveness of eliminating explosions and removing unnecessary hardware from the environment Ref. 1, 4, 5) as mitigation techniques. These results, obtained with models that are validated using measurements of the current environment, clearly demonstrate both the long-term necessity and effectiveness of debris mitigation measures. Current study efforts are addressing the cost effectiveness issues that need to be addressed to ascertain when and how such measures should be introduced.

In the current environment, spacecraft failures arising from collisions with debris occur with probabilities of tenths to hundredths of a percent per year depending on the mission orbit altitude and on the size of debris that could cause critical damage. In the next 100 years current models show that, unless measures are taken to limit the generation of debris, the probabilities will grow to a few tenths to a few percent per year and will be increasing rapidly and thus will approach component failure probabilities as a cause for loss of spacecraft. The guidelines defined in the Handbook provide limits on debris generation that will halt the growth of the debris environment and ensure that debris does not become an increasingly significant cost factor for future space operations.

Using the Handbook a program manager is able to assess the potential debris risk the program represents to other users of space in five broad areas and if there is hardware that will reenter the atmosphere, the level of risk to man associated with that reentry. The risk to a given spacecraft or upper stage is, of course, a consequence of these debris risk factors as contributed by other operators. The areas of concern are:

1. Leaving operational debris in the environment. Such debris, while small in number, is generally larger than 1cm, and represents a risk of single event failure to operating spacecraft. These objects will remain in orbit for months to years if left at low altitude, for tens to hundreds of years if released at altitudes typical for sun-synchronous missions, and for much longer times for release above this altitude.

2. Experiencing explosions in orbit. Explosions produce a number of large debris satellites, capable of causing single event failure of a spacecraft, as well as numerous small debris fragments posing a risk of degraded performance. The velocities imparted to the debris on breakup may create a significant risk to spacecraft operating hundreds of kilometers above or below the breakup altitude, and may place debris in orbits with very long lifetimes.

3. Experiencing a catastrophic breakup during mission operations as a result of collision with a large debris object. This is primarily a problem for programs having large spacecraft with long mission life.

4. Failing to remove a structure from a high value region of space at the end of useful life, so that it becomes a potential source of small debris that could affect future space operations in that region. Failure to remove non-functional objects from orbit might be the normal operational procedure (as it is in most cases today) or occur because control of a structure is lost during its mission life, either from design failure or collision with small debris.

5. Creating an unacceptably large risk to man as a result of atmospheres reentry.

The Handbook supports programs with input needed to assess spacecraft vulnerability to impact with small manmade or meteoroid debris by providing flux and flux directionality models for both the meteoroid and manmade debris environments. The directionality models include velocity as well as directional distributions, so that penetration fluxes can also be calculated onto oriented spacecraft surfaces. This assessment indicates the protection required to maintain functionality as well as to preclude debris generation.

TABLE 1. EXAMPLE GUIDELINE: EXPLOSIONS FROM ON BOARD STORED ENERGY

GUIDELINE

1. All fluid containers and pressurized volumes should be vented after completion of function. "Completion of Function" includes post-mission deorbit maneuvers or maneuvers to disposal orbits, where such maneuvers are suggested by the guidelines. For launch vehicles and upper stages, all residual fuels and oxidizers and all high pressure fluid elements not needed for post-mission disposal should be vented as soon as such an operation does not pose an unacceptable risk to the payload.

2. Where the probability of explosion induced by stored energy sources during the mission life for a program can be estimated with reasonable cost and analytic effort, that probability, denoted P_{SEE}, should be limited by

$$P(d|LIE) * P_{SEE} \leq 0.0001$$

$P(d|LIE)$ is the conditional probability of damage to an operating spacecraft given that a low intensity explosion has occurred. It depends on the mass and altitude of the spacecraft experiencing the explosion, and is given by

$$P(d|LIE) = 1.0 - EXP(-N_D^{LIE})$$

N_D^{LIE} is the expected number of impacts between explosion debris fragments larger than 1cm and some operating spacecraft, and is given by

$$N_D^{LIE} = \begin{cases} 0.0001*M(kg) & H \geq 600 \text{ km} \\ 10^{(0.0113*H-10.80)}*M(kg) & H \leq 600 \text{ km} \end{cases}$$

M is the vehicle mass in kilograms and H is the mission orbit apogee altitude in kilometers. When $P(d|LIE)$ is less than 0.0001, P_{SEE} may be as large as 1.

Note: The guideline was derived by placing an upper bound of 10^{-6} on the probability of damage to any given operating spacecraft arising from the launch of a structure capable of experiencing a low intensity explosion. Damage to a spacecraft is defined to be impact with a 1cm or larger debris fragment from the explosion. This probability is the conditional probability of damage given an explosion occurring, $P(d|LIE)$, times the probability of an explosion occurring, P_{SEE}. The conditional probability, $P(d|LIE)$, which depends on breakup altitude and mass of the object experiencing the explosion, is discussed in Appendix C. Using the guideline, there is a 2×10^{-6} probability per launch that a large explosion fragment will collide with another large object in the environment, creating a substantial amount of collisional debris fragments.

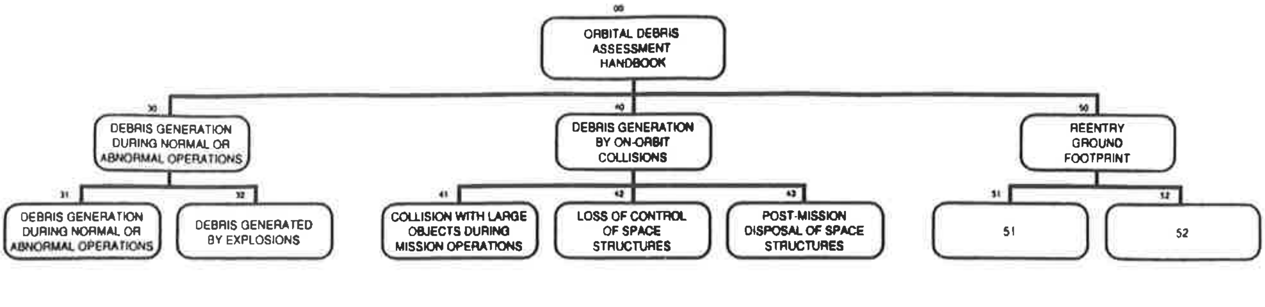

Figure 1. Top level Structure For Analysis Sections of Handbook

The structure of the Handbook software parallels that of the Handbook. The five top level sections correspond to the five guideline areas; and the correspondence between software sections and Handbook sections is presented in Table 2. The software is documented more completely in its own volume of documentation, and the menu structure and screen selections make the software easy to use.

2.2 Overview of Handbook Guidelines

The guidelines and supporting analysis tools in the Handbook are grouped into five general areas. These five areas are as follows:

1. Control of Debris Released During Normal Operations.

NASA programs and projects will assess and limit the amount of debris released during normal operations.

2. Control of Orbital Debris Generation by Explosions.

NASA programs and projects will assess and limit the probability of accidental explosion by eliminating sources of stored energy at the end of operations. Also, the effect of intentional explosions on other users of space will be limited.

3. Control of Debris Collision Risk During Mission Operations.

NASA programs and projects will assess and limit: (1) the probability of catastrophic impact with other space systems or large debris, and (2) the probability of failure of space structures/systems resulting in loss of control, so that the structure becomes vulnerable to catastrophic collision for extended periods of time.

4. Post-Mission Disposal of Space Structures.

NASA programs and projects will plan for the disposal of launch vehicles, upper stages, and payloads at the end of mission life. The post-mission disposal options include maneuver into an orbit in which atmospheric drag will remove the structure in a short time or maneuver to one of a set of defined disposal orbits. For many low altitude programs (in general, those having mission orbit perigee altitude ˜<500km) there will be no debris control requirement for post-mission disposal (but there may be a requirement when the reentry footprint is considered).

5. Analysis of Ground Footprints for Reentering Structures and Debris

NASA spacecraft and upper stages will assess the potential for a significant ground footprint on reentry and will either control their reentry point so as to not present a threat to the ground or establish procedures or designs to reduce the footprint.

Although specific guidelines are currently being reviewed within NASA prior to release for general outside review, the general characteristics of the guidelines are presented in Table 3. The guidelines were defined to limit the risk to operating spacecraft, either directly by limiting the amount of debris placed in the environment or indirectly by limiting the amount of non-functional mass in large objects remaining in orbit and the probability of either explosive or collisional breakups. Because removal of objects from orbit using atmospheric drag is one of the mitigation measures recommended for low earth orbit and highly eccentric orbit, the Handbook also provides support to assess the reentry risk.

2.2 Overview of Handbook Guidelines

The guidelines and supporting analysis tools in the Handbook are grouped into five general areas. These five areas are as follows:

1. Control of Debris Released During Normal Operations.

NASA programs and projects will assess and limit the amount of debris released during normal operations.

2. Control of Orbital Debris Generation by Explosions.

NASA programs and projects will assess and limit the probability of accidental explosion by eliminating sources of stored energy at the end of operations. Also, the effect of intentional explosions on other users of space will be limited.

3. Control of Debris Collision Risk During Mission Operations.

NASA programs and projects will assess and limit: (1) the probability of catastrophic impact with other space systems or large debris, and (2) the probability of failure of space structures/systems resulting in loss of control, so that the structure becomes vulnerable to catastrophic collision for extended periods of time.

4. Post-Mission Disposal of Space Structures.

NASA programs and projects will plan for the disposal of launch vehicles, upper stages, and payloads at the end of mission life. The post-mission disposal options include maneuver into an orbit in which atmospheric drag will remove the structure in a short time or maneuver to one of a set of defined disposal orbits. For many low altitude programs (in general, those having mission orbit perigee altitude ˜<500km) there will be no debris control requirement for post-mission disposal (but there may be a requirement when the reentry footprint is considered).

5. Analysis of Ground Footprints for Reentering Structures and Debris

NASA spacecraft and upper stages will assess the potential for a significant ground footprint on reentry and will either control their reentry point so as to not present a threat to the ground or establish procedures or designs to reduce the footprint.

Although specific guidelines are currently being reviewed within NASA prior to release for general outside review, the general characteristics of the guidelines are presented in Table 3. The guidelines were defined to limit the risk to operating spacecraft, either directly by limiting the amount of debris placed in the environment or indirectly by limiting the amount of non-functional mass in large objects remaining in orbit and the probability of

2.3 Current Status/Projected Activity

Much of the technical support for debris analysis required in the Handbook has been developed. A major effort has been required to adapt the concepts to be easily understood by a person not familiar with the orbital debris problem, and to make the Handbook function, in fact, as a handbook and not a debris tutorial.

Consideration of risk associated with reentry is just beginning to be included in the Handbook. Parametric models are being developed to allow programs to determine for general materials and structures the extent of the ground footprint. This work will then use previously performed analyses on reentry risk as a function or orbit inclination and total cross-sectional area of debris to survive to the ground to assess reentry risks.

The Handbook is scheduled for technical review outside of NASA after completion of internal review in Spring 1993. Handbook software to run on a desktop computer will also be provided for the technical review. A workshop for industry review and comment is scheduled to occur at NASA/JSC in Summer 1993. Inclusion of industry comments and delivery of the completed Handbook is scheduled for Autumn 1993.

3.0 CONCLUSIONS

A Handbook is being prepared to support implementation of the NASA policy to limit orbital debris generation as stated in NMI 1700.xx. This Handbook will reduce the time and costs for performing such assessments. The Handbook is structured around guidelines for control of direct or indirect debris generation processes, and contains methodologies for conducting assessments and information on use of the Handbook software to supplement information in the Handbook proper.

The Handbook is nearing release for review outside of NASA. Within the next 5 months review comments will be solicited from all interested parties. This review will focus on an industry review workshop to be held at NASA/JSC in August. The Handbook is scheduled for delivery to the NASA Office of Safety and Mission Quality in Autumn 1993.

4.0 REFERENCES

1. Loftus, J., R. Reynolds, and P. Anz-Meador. Space Debris Minimization and Mitigation Plans and Practices, Published in the Proceedings of the Space Debris Forum, Sponsored by the Japan Society for Aeronautics and Space Sciences, Tokyo, May 15, 1992.

2. Kessler, D. Collisional Cascading: The Limits of Population Growth in Low Earth Orbit, Advances in Space Research, 11, 12, 63-66, 1991.

3. Eichler, P. Analysis of the Necessity and Effectiveness of Countermeasures to Prevent a Chain Reaction of Collisions, Proceedings of the IAF Congress Montreal, Paper IAA-91-591, October, 1991.

4. Rex, D. The Effectiveness of Debris reduction Measures, Presented at the 1992 World Space Congress, Paper B.8 - M.3.04, August, 1992.

5. Reynolds, R., D. Kessler, and J. Loftus. Assessing the Effectiveness of Techniques to Limit Orbital Debris Generation, to be presented at SPIE/Aerospace Science and Sensing '93, Paper 1951-34, April, 1993.

TABLE 2. CORRESPONDENCE BETWEEN HANDBOOK SOFTWARE SECTIONS AND HANDBOOK ASSESSMENT CATAGORIES

ASSESSMENT CATEGORY	SUPPORTING HANDBOOK SOFTWARE UNIT
1. Debris Released During Normal Operations	1. Assessment of Debris Released During Normal Operations
2. Debris Generated by Explosions	2. Evaluation of Explosions
3. Collisions with Large Objects During Mission Operations	3. Collision Avoidance
4. Collisions with Debris Causing Loss of Control	4. Spacecraft Hazard Analysis
5. Post Mission Disposal of Space Structures	5. Post Mission Performance Analysis
6. Assessment of Reentry Risks	6. Reentry Analysis

TABLE 3. SYNOPSIS OF HANDBOOK GUIDELINES

Debris Event	Nature of Guideline
Release operational debris	limit number, size, and orbit lifetime
Accidental explosions	remove on-board stored energy at end of mission life; limit probability of explosion based on mission orbit altitude and mass of object
Intentional explosions	limit altitude; perform risk analysis during program development and immediately before event for active spacecraft
Solid rocket motor firing	limit lifetimes of >1mm products in LEO; limit interaction with GEO systems
Catastrophic collision in	use collision avoidance if probability is large LEO enough that debris causes a risk to other operating spacecraft
Catastrophic collision in	Systems in low inclination GEO orbit avoid GEO stable plane systems
Damaging collisions with	limit probability of occurrence based on orbit small debris leading altitude and mass of spacecraft
Hardware in orbit after	LEO/GTO - remove from orbit; completion of mission MEO - move away from 12 hour orbit; GEO - (1) move to general super-GEO disposal region (2) move to super-GEO stable plane (3) move to GEO stable plane
Re-entry	limit risk arising from ground footprint