Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs

AERONAUTICS AND SPACE ENGINEERING BOARD
NATIONAL RESEARCH COUNCIL
THE NATIONAL ACADEMIES

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Presentation Outline

- Origin of Study
  - Statement of Task
  - Committee Membership
  - Meeting Schedule
- Background
- Findings & Recommendations
  - Review NASA's MMOD Programs and Efforts
  - Recommend Changes in Effort or Focus
  - New MMOD Areas for NASA to Pursue

Origin of the Study

- NRC conducted several foundational studies on Orbital Debris in the 1990's
- These studies helped shape NASA's current meteoroid and orbital debris (MMOD) programs
- OMB and OSTP asked NASA to have the NRC conduct a new study to determine if there are gaps or areas that require greater (or lesser) emphasis and resources

Statement of Task

The National Research Council, under the auspices of the Aeronautics and Space Engineering Board, will establish an ad hoc committee to assess NASA's orbital debris programs and provide recommendations on potential opportunities for enhancing their benefit to the nation's space program.

Statement of Task

- The committee will:
  - Review NASA's existing efforts, policies, and organization with regards to orbital debris and meteoroids, including efforts in the following areas:

    Modeling and simulation, Detection and monitoring, Protection, Mitigation, Reentry, Collision assessment , risk analysis and launch collision avoidance, Interagency cooperation, International cooperation, and Cooperation with the commercial space industry.

  - Assess whether NASA should initiate work in any new orbital debris or meteoroid areas.
  - Recommend whether NASA should increase or decrease effort in or change the focus of any of its current orbital debris or meteoroid efforts to improve the programs' ability to serve NASA and other national and international activities.
- The committee should assume that the programs will be operating in a constrained budget environment.

Committee Membership

- **Donald J. Kessler, Chair**
  NASA (retired)
- **Kyle T. Alfriend**
  Texas A&M University
- **Michael J. Bloomfield**
  Oceaneering Space Systems
- **Peter Brown**
  University of Western Ontario
- **Ramon L. Chase**
  Booz Allen Hamilton
- **Sigrid Close**
  Stanford University
- **Joanne I. Gabrynowicz**
  National Center for Remote Sensing, Air, and Space Law, University of Mississippi
- **George J. Gleghorn, Vice Chair**
  TRW Space and Technology Group (retired)
- **Roger E. Kasperson**
  Clark University
- **T.S. Kelso**
  Analytical Graphics, Inc.
- **Molly K. Macauley**
  Resources for the Future
- **Darren S. McKnight**
  Integrity Applications, Inc.
- **William P. Schonberg**
  Missouri University of Science and Technology

Meeting Schedule

- Meeting 1: December 13-15, 2010
  - Received overview briefing of NASA programs from researchers and managers (OSMA, ODPO, MEO, CARA, HVIT)
  - Discussed SOT with OMB
  - Received presentations from ESA, Air Force Space Command, Aerospace Corporation
- Meeting 2: January 19-21, 2011
  - Received detailed briefings regarding NASA's efforts, particularly those undertaken by NASA's Orbital Debris Program Office (NASA HQ, JSC, KSC, MSFC, ODPO, MEO, CARA, COLA, HVIT)

Meeting Schedule

- Meeting 3: March 9-11, 2011
  - Included 1.5 day workshop
  - *Summary of the Workshop to Identify Gaps and Possible Directions for NASA's Meteoroid and Orbital Debris Programs*
  - In attendance: NASA MMOD program leads, FAA, NOAA, Department of State, FCC, OSTP, Lockheed Martin, XL Insurance, Iridium Satellite Communications
- NASA Ames Briefing during April 22 Telecon
- Meeting 4: April 25-27, 2011
  - Dedicated to the writing of the report

Background

- Fundamental technical issue of Orbital Debris: 2.5 Million kilograms of man-made objects in LEO
  - Generates a large amount of smaller debris
  - Collisions are at hypervelocity speeds
  - Small debris has become a significant hazard to spacecraft
  - Fragmentation events increase the amount of small debris

Overview of NASA's Orbital Debris Program

- Goals
  - Preserve the space environment
  - Support U.S. programs to achieve their desired mission success while preserving the environment
- Approach
  - Define the environment with measurements and models
  - Develop and test mitigation and remedial strategies using models and measurements
  - Coordinate with other national and international agencies.

Orbital Debris Program Elements

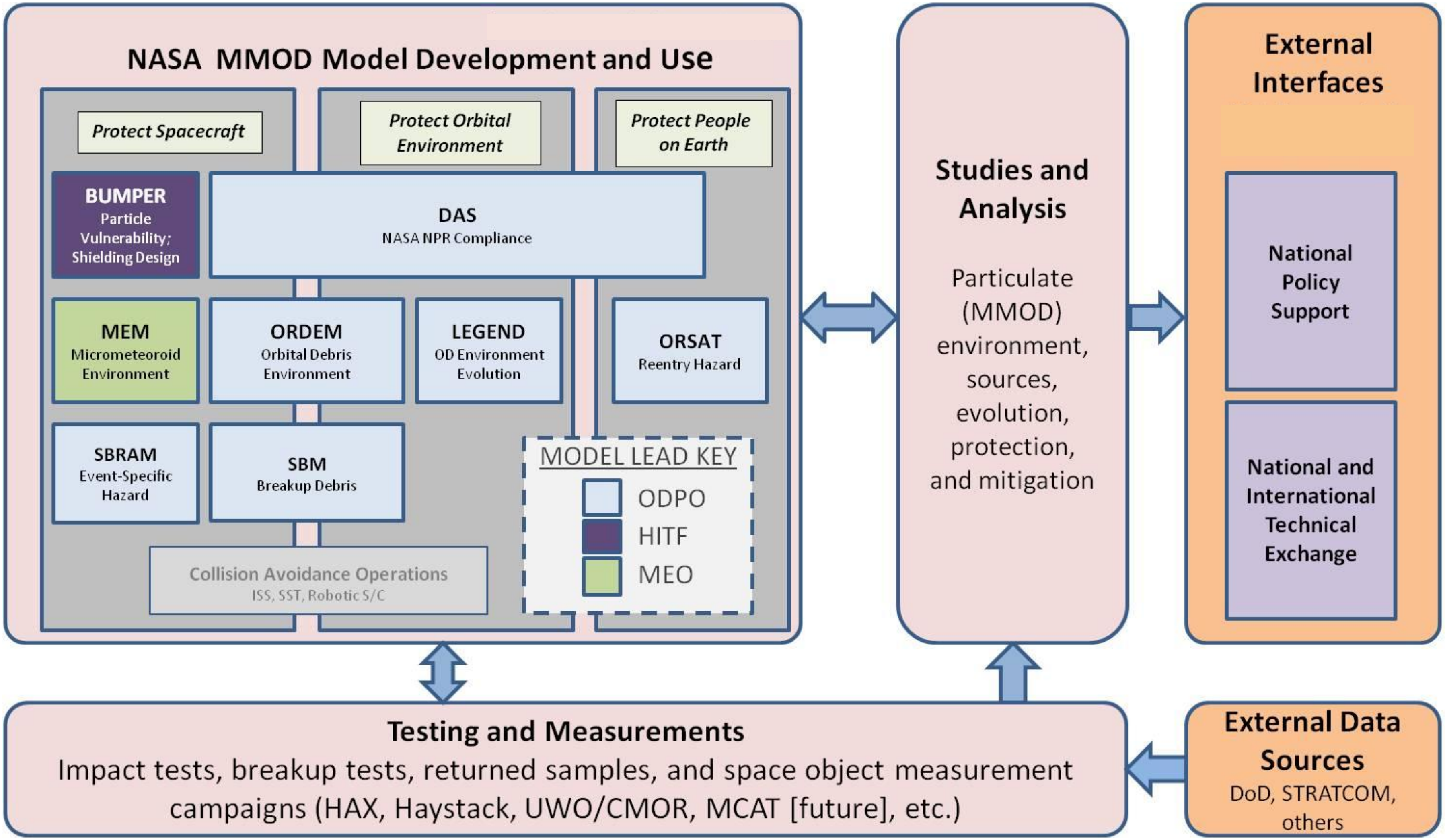

Figure 1.1 from the report.

Overview of Program Accomplishments

- Inter-Agency Space Debris Coordination Committee
- Mitigation procedures accepted internationally
- Working relationship with US Agencies
- Operational support ranges from shielding design to collision avoidance
- Program spread through several centers and DoD
- Current environment requires remediation
- Increasing responsibility from National Space Policies beginning in 1988 through 2010

Report Structure

1. Introduction and Historical Background
2. Orbital Debris Environment: Detection and Monitoring
3. Orbital Debris Modeling and Simulation
4. The Meteoroid Environment and Its Effects on Spacecraft
5. Risk Assessment and Uncertainty
6. Spacecraft Protection in the MMOD Environment
7. Mitigation of Orbital Debris
8. Hazards Posed by Orbital Debris Reentry
9. Conjunction Assessment Risk Analysis and Launch Collision Avoidance
10. Spacecraft Anomalies
11. Issues External to NASA
12. Management and Organization Issues
13. Preparing for the Future
14. Compiled List of Findings and Recommendations

Findings & Recommendations

THE FINDINGS AND RECOMMENDATIONS IN THE REPORT COVER A WIDE RANGE OF TOPICS CONCERNING SCIENTIFIC, ENGINEERING, AND POLICY ISSUES. THE FOLLOWING FINDINGS AND RECOMMENDATIONS ARE AMONG THE MOST PRESSING IN THE REPORT, AND ARE GROUPED AROUND THE THREE OVER-ARCHING TASKS FOUND IN THE STUDY'S STATEMENT OF TASK. HOWEVER, THE EXCLUSION OF FINDINGS AND RECOMMENDATIONS FROM THESE SLIDES DOES NOT MEAN THAT THOSE ARE NOT OF GREAT IMPORTANCE.

Task 1

Review NASA's existing efforts, policies, and organization with regards to orbital debris and meteoroids.

Doing More With Less

- **Finding**: **NASA's meteoroid and orbital debris programs have used their resources responsibly and have played an increasingly essential role in protecting the safety of both crewed and uncrewed space operations.**

- **Finding**: **The increasing responsibilities given to NASA's meteoroid and orbital debris programs have put pressure on the programs' allotted resources. The increasing scope of work, complexity and severity of the debris and meteoroid environment are outpacing the decreasing funding levels of NASA's MMOD programs in real dollars.**

Task 2

Assess whether NASA should initiate work in any new orbital debris or meteoroid areas.

Strategic Plan

Recommendation: **NASA should develop a formal strategic plan that provides the basis for prioritizing judgments in the allocation of funds and effort over various program needs. Box S.1 is a selection of potential research needs and management issues to be considered. The strategic plan should consider short- and long-term objectives, a schedule of benchmark achievements to be accomplished, and priorities among them. Stakeholders should be engaged to help develop and review this plan. Finally, the MMOD strategic plan should be revised and updated at regular intervals.**

Box S.1: Research Needs and Management Issues To Be Considered in the Formulation of an MMOD Strategic Plan

Throughout this report, the committee identifies various areas of potential research and a number of management actions that would strengthen NASA's MMOD programs. Adoption of a strategic plan of the sort envisioned by the committee would require evaluation and prioritization of these areas and activities.

See slides 29 thru 31 for a list of 22 areas and activities to be considered in the strategic plan.

Task 3

Recommend whether NASA should increase or decrease effort in or change the focus of any of its current orbital debris or meteoroid efforts to improve the programs' ability to serve NASA and other national and international activities.

Spacecraft Failures and Debris Monitoring

<u>Recommendation</u>: NASA should initiate a new effort to record, analyze, report, and share data on spacecraft anomalies in order to better quantify the risk from particulates too small to be cataloged yet large enough to disrupt space operations. The results of this effort will provide general insights into the effect of meteoroids and orbital debris on operational space systems. Eventually, this effort could provide data to upgrade the MMOD models— the Meteoroid Environment Model, Orbital Debris Environment Model, and BUMPER.

NASA MMOD Programs Management Structure

- **<u>Finding</u>: NASA's management structure has not kept pace with the expanding responsibilities of its MMOD programs. Consequently, the MMOD programs do not have a single management and budget point that can efficiently coordinate all of the current and planned activities and establish clear priorities.**

- **<u>Finding</u>: Nearly all of NASA's MMOD programs are only one person deep in staffing. This shortage of staffing makes the programs highly vulnerable to budget reductions or personnel changes. Further reductions in real budgetary support over the coming years could threaten the viability and scope of ongoing programs.**

- **<u>Recommendation</u>: NASA should review the current management structure of its MMOD programs in order to achieve better coordination, provide improved central decision making, and establish a framework for setting priorities. This framework should include a major interface with Congress, other federal and state agencies, and the public.**

Looking to the Future

- **Finding: Debris removal activity that involves selecting and removing any given object—debris or otherwise—from space, crosses crucial national and international legal thresholds.**

- **Recommendation: NASA should lead public discussion of the space debris problem to emphasize debris as a long-term concern for society that must continue to be addressed today. Necessary steps include improvements in long-term modeling, better measurements, more regular updates to debris environmental models, and other actions to better characterize the long-term evolution of the debris environment.**

- **Recommendation: NASA's meteoroid and orbital debris programs should engage the NASA General Counsel's Office and, through that office, the U.S. State Department regarding the legal requirements and diplomatic aspects of active debris removal.**

Questions?

Backup Slides

BOX S.1 DETAILS

AND

REPORT FINDINGS AND RECOMMENDATIONS

Box S.1: Research Needs and Management Issues To Be Considered in the Formulation of an MMOD Strategic Plan

Chapters 2 thru 4

1. Perform radar cross-section calibrations using fragments from a large range of materials used in modern satellites and rocket bodies, as well as non-fragmentation debris. (Chapter 2)
2. Expand the environment measurement program to include use of in situ sensors to monitor the flux of debris smaller than a few millimeters. (Chapter 2)
3. Expand efforts to more accurately model sources of. (Chapter 3)
4. Develop criteria or a schedule for the regular release of updates to its orbital debris- and meteoroid-related models. (Chapter 3)
5. Establish a base effort to evaluate major environmental uncertainties in three areas: (a) meteoroid velocity distributions, (b) flux of meteoroids at larger sizes (greater than 100 microns), and (c) impact plasma effects. (Chapter 4)
6. Adopt a single model of the meteoroid environment for official use. (Chapter 4)
7. Pursue improving the understanding of the hazards posed by interplanetary meteoroids. (Chapter 4)
8. Expand research on meteoroids to include an understanding of the possible link between spacecraft electrical anomalies and major meteor showers. (Chapter 4)

Box S.1: Research Needs and Management Issues To Be Considered in the Formulation of an MMOD Strategic Plan

Continued, Chapters 5 thru 8

9. Perform a broad integrative analysis of the various risks posed by meteoroids and orbital debris (whether probabilistic risk analysis or some alternative). (Chapter 5)
10. Identify major areas of uncertainty in current environmental models and risk assessments, and develop test plans and analyses to reduce that uncertainty. (Chapter 5)
11. Undertake an effort to refine models for predicting impact damage using a statistics-based approach. (Chapter 6)
12. Undertake an effort to re-derive the ballistic limit equations in the BUMPER code using a statistics-based approach that would provide information regarding uncertainty bounds and/or confidence intervals. (Chapter 6)
13. Increase efforts to characterize the damage resulting from impacts of orbital debris of various particle shapes and densities. (Chapter 6)
14. Expand program plans to include the technology, political and legal considerations necessary to increase international cooperation on mitigation and remediation measures to stabilize the orbital debris environment. (Chapter 7)
15. In regard to re-entry risks, re-examine how thresholds for ground injury effects are estimated and provide confidence bounds and uncertainty assessments. (Chapter 8)

Box S.1: Research Needs and Management Issues To Be Considered in the Formulation of an MMOD Strategic Plan

Continued, Chapters 9 thru 13

16. Develop a research plan for (a) assessing the impact of the inaccuracy in the uncertainty in computing the probability of collision and the ensuing risk assessment and (b) improving the accuracy of the computation of the probability of collision in the presence of these uncertainty errors. (Chapter 9)
17. Initiate an effort to record, analyze, report, and share satellite anomalies in order to better quantify the risk from orbital debris particulates too small to be cataloged yet large enough to disrupt space operations. (Chapter 10)
18. Continue to engage the private sector, U.S. federal agencies, and international agencies in developing cooperation and political will to effectively address issues regarding orbital debris activities. (Chapter 11)
19. Identify budget requirements and areas of responsibilities, including personnel and a single point of contact, for maintaining a viable program as budgets and personnel change. (Chapter 12)
20. Schedule periodic technical assessments written for policy makers and stakeholders. (Chapter 12)
21. Continue to emphasize the long-term objectives of the MMOD programs through public discussions and improved long-term models. (Chapter 13)
22. Monitor and inventory the costs of debris avoidance, mitigation, surveillance, and reporting over time. (Chapter 13)

Chapter 1: Introduction and Historical Background

- **Finding: NASA's meteoroid and orbital debris programs have used their resources responsibly and have played an increasingly essential role in protecting the safety of both crewed and uncrewed space operations.**
- **Finding: Finding: The increasing responsibilities given to NASA's meteoroid and orbital debris programs have put pressure on the programs' allotted resources. The increasing scope of work, and the complexity and severity of the debris and meteoroid environment are outpacing in real dollars the decreasing funding levels of NASA's MMOD programs.**

Chapter 2:
Orbital Debris Environment: Detection and Monitoring

- **<u>Finding</u>: The current lack of radar cross-section calibrations using fragments from a larger range of materials used in modern satellites and rocket bodies, as well as non-fragmentation debris, represents a significant source of uncertainty in interpreting key measurements of the orbital debris environment.**
- **<u>Finding</u>: NASA's orbital debris programs do not include the capability to monitor with in situ instrumentation the penetrating flux of objects smaller than a few millimeters. Data collected by in situ monitoring could be used to resolve uncertainties in measurements made remotely, to help identify new sources of debris, and to provide clues to the causes of spacecraft anomalies.**

Chapter 3: Orbital Debris Modeling and Simulation

- **<u>Finding</u>: Correctly characterizing the shape and material properties of orbital debris is critical to correlating the results of ground-based satellite impact tests with radar cross-section data and thus to predicting the damage caused by debris particles, yet there has been little effort to include realistic effects of shape in the Standard Breakup Model. These enhancements would also serve to improve BUMPER's accuracy in predicting risks.**
- **<u>Recommendation</u>: The NASA Orbital Debris Program Office should expand its efforts to more accurately incorporate data on sources of debris into the Standard Breakup Model, especially (1) empirical results from recent major on-orbit collisions, (2) data from laboratory rocket body collision tests (which need to be planned and conducted), (3) results from hypervelocity impact tests with payloads using newer construction methods and materials, and (4) enhanced data on fragment shape characteristics.**
- **<u>Recommendation</u>: NASA's Orbital Debris Program Office should release the next version of the Orbital Debris Environment Model as soon as possible and provide updates on a regular basis or as often as required as a result of major changes to the environment or improved characterization of the orbital debris environment, including characterization of debris shape, as applicable.**

Chapter 4: The Meteoroid Environment and Its Effects on Spacecraft

- **<u>Finding</u>: The models used to relate measurements of plasma to fundamental parameters of a meteoroid contain large uncertainties and errors. These models include, but are not limited to, electromagnetic scattering models, luminous emission models, and meteoroid fragmentation models.**
- **<u>Finding</u>: Because the scientific community infers the properties of a meteoroid indirectly from its effects on the atmosphere (a meteor) or the effects of its impact on a satellite, it is imperative to understand observational biases in the detection of these secondary effects inherent in each instrument.**
- **<u>Finding</u>: The Meteoroid Environment Model incorporates in its predictions the latest available data on the meteoroid environment, including the directionality and full velocity distribution of the meteoroids. It is currently the NASA model that is most consistent with the known meteoroid environment, although some major uncertainties still remain.**
- **<u>Recommendation</u>: The NASA meteoroid and orbital debris programs should establish a baseline effort to evaluate major uncertainties in the Meteoroid Environment Model regarding the meteoroid environment in the following areas: (1) meteoroid velocity distributions as a function of mass; (2) flux of meteoroids of larger sizes (>100 microns); (3) effects of plasma during impacts, including impacts of very small but high-velocity particles; and (4) variations in meteoroid bulk density with impact velocity.**

Chapter 4:
The Meteoroid Environment and Its Effects on Spacecraft

- **Finding: The earlier SSP 30425 meteoroid model does not reproduce existing observational meteoroid data with the same fidelity as the Meteoroid Environment Model. Numerous disparate sources of data have been fused to produce the current meteoroid flux model used by NASA sometimes incorporating differing underlying assumptions.**
- **Finding: The Meteoroid Environment Model currently does not extend to prediction of the meteoroid environment in the outer solar system and the measurements it incorporates are poorly constrained in the cis-martian region.**
- **Recommendation: An effort should be made to re-examine earlier data used in the Grün Interplanetary Flux Model and to reconcile the data with more recent measurements in the literature on meteoroid flux, and a technical evaluation should be undertaken to synthesize and document such data as it is incorporated into the Meteoroid Environment Model (MEM). Updates of the MEM and technical development should follow a technical pathway as rigorous as is being taken for updates of the Orbital Debris Environment Model.**
- **Recommendation: NASA should adopt the Meteoroid Environment Model for agency-wide official use and extend its capabilities to the outer solar system.**

Chapter 5:
Risk Assessment and Uncertainty

- **<u>Finding</u>: NASA's MMOD risk assessment processes have evolved beyond focusing primarily on the damage to spacecraft from collisions with debris that are too small to track to incorporating a more complete range of risks. More remains to be accomplished, however, including the need in some cases for more measurements as parameters for risk analyses. As gaps are filled, NASA's efforts in MMOD can progress toward ever more integrative risk assessment in which all sources and types of risk are modeled and assessed.**
- **<u>Recommendation</u>: Although NASA should continue to allocate priority attention and resources to collision risks and conjunction analysis, it should also work toward a broad integrative risk analysis to obtain a probabilistic risk assessment of the overall risks present in the MMOD domain in which all sources of risks can be put in context.**
- **<u>Finding</u>: The calculation and communication of information about uncertainty are critical to properly assessing operational alternatives based on calculated risks posed by orbital debris.**
- **<u>Recommendation</u>: NASA's meteoroid and orbital debris programs should increase their efforts to reduce the uncertainty and variability in models through acquisition of measurements (and where necessary, to do testing and analysis) for continually improving assessment of risk and characterization of uncertainty. Together with its MMOD efforts, NASA should continue to advance the agency's efforts to present information on uncertainty in risk analyses. Special attention should be given to maximizing public understanding of uncertainty analysis through peer-reviewed papers and other publications.**

Chapter 6: Spacecraft Protection in the MMOD Environment

- **<u>Finding</u>: The BUMPER program was never designed to fully address the probability of spacecraft failure following penetration by a meteoroid(s) or pieces of orbital debris.**
- **<u>Recommendation</u>: NASA's own MSCSurv code might offer insights for development of an expanded, improved MMOD risk analysis code that fully addresses the risk to a valuable spacecraft following an MMOD impact and, as such, should be coupled with results from BUMPER for use as needed.**
- **<u>Finding</u>: It is not possible to obtain uncertainty bounds and/or confidence intervals as part of the current procedures being used to derive damage predictor equations in BUMPER.**

Chapter 6: Spacecraft Protection in the MMOD Environment

- **<u>Recommendation</u>: Considering the critical need to develop overall uncertainty bounds for predictions of MMOD impacts (which in turn could be used in a probabilistic risk assessment), NASA should refine its damage prediction models so that they include uncertainty bounds and/or confidence intervals.**
- **<u>Finding</u>: Using aluminum spheres to develop ballistic limit equations for risk assessments for spacecraft may not accurately portray the range of damage likely from impact with an orbital debris particle of any given characteristic size and thus may result in a non-optimum design of the spacecraft's MMOD protection systems.**
- **<u>Recommendation</u>: A priority in the next release of the Orbital Debris Environment Model and Standard Breakup Model should be the inclusion of shape characteristics in the particle distributions to more accurately portray the range of potential damage from impact with orbital debris.**

Chapter 7: Orbital Debris Mitigation

- **<u>Finding</u>: NASA's current orbital debris programs are recognized both nationally and internationally as leaders in providing support for defining the environment and related impact hazards associated with orbital debris, and mitigation techniques to effectively minimize the hazards associated with the current and future orbital debris environment.**
- **<u>Finding</u>: Most relevant federal agencies accept all or some of the components of NASA's orbital debris mitigation and prevention guidelines.**
- **<u>Finding</u>: Enhanced mitigation standards or removal actions are likely to be necessary to limit the growth in the orbital debris population. Although NASA's orbital debris programs have identified the need for orbital debris removal, the necessary economic, technology, testing, political, or legal considerations have not been fully examined, nor has analysis been done to determine when such technology will be required.**

Chapter 8: Debris Reentry Hazard

- **<u>Finding</u>: NASA's Object Reentry Survival Analysis Tool provides results as point estimates without confidence bounds or uncertainty estimates.**
- **<u>Recommendation</u>: In regard to debris reentry risk, NASA should provide confidence bounds on and uncertainty estimates of the resulting risk levels for use in both the Debris Assessment Software and Object Reentry Survival Analysis Tool.**
- **<u>Finding</u>: The reentry hazard programs used by NASA and ESA to determine the risk to people on the ground from reentering debris differ in how those thresholds are defined. NASA's Object Reentry Survival Analysis Tool defines a "casualty" as personal injury, whereas ESA models equate a "casualty" with death.**
- **<u>Recommendation</u>: NASA should update the Object Reentry Survival Analysis Tool so that it provides the probabilities of both injury *and* death as standard outputs.**

Chapter 9: Conjunction Assessment Risk Analysis and Launch Collision Avoidance

- **<u>Finding</u>: The computation of the probability of collision for use in an assessment of risk requires the uncertainty parameters in the orbits of the two objects at conjunction, and assumes that these uncertainties are represented by a Gaussian distribution. Research has shown that the uncertainty distribution typically is Gaussian for several days, but when propagating for more than 2 to 3 days it may no longer be Gaussian. In addition, the uncertainties provided by the JSpOC are known to be usually too small, and the probability of collision can be very sensitive to errors in the size of the uncertainty.**
- **<u>Recommendation</u>: NASA should develop a research plan for (a) assessing the impact of inaccuracy in the uncertainty on computations of the probability of collision and on the ensuing risk assessment, and (b) improving the accuracy of the computation of the probability of collision, given the presence of these uncertainty errors.**
- **<u>Finding</u>: The large uncertainties in the launch dispersions (deviations from a planned trajectory) that yield a probability of collision of less than 10-5 translate to a very low return on investment in launch collision avoidance (COLA), and funds could probably be used more effectively in some other area of debris mitigation. However, in the event of a collision during launch, the political realities of potentially having done nothing probably mean that the use of COLA needs to continue, especially for crewed launches.**

Chapter 10: Spacecraft Anomalies

- **<u>Finding</u>: Spacecraft anomalies are a direct measurement of both the state of the particulate environment in space and the adequacy of the spacecraft design. However, no formal recording, analyzing, sharing, and reporting procedures exist to take advantage of data on spacecraft anomalies despite that data's potential as valuable information about particulates in a critical size range that is typically not sampled continuously.**
- **<u>Recommendation</u>: NASA should initiate a new effort to record, analyze, report, and share data on spacecraft anomalies in order to better quantify the risk from particulates too small to be cataloged yet large enough to disrupt spacecraft operations. The results of this effort would provide general insights into the effects of meteoroids and orbital debris on operational space systems. Eventually, this effort could provide data to upgrade current MMOD models— the Meteoroid Environment Model, Orbital Debris Environment Model, and BUMPER.**

Chapter 11: Issues External to NASA

- **<u>Finding</u>: NASA's Orbital Debris Mitigation Standard Practices, including the "25-year rule," and NASA's Procedural Requirements for Limiting Orbital Debris do not uniformly apply to non-NASA missions, launches, and payloads.**
- **<u>Recommendation</u>: NASA should continue to engage relevant federal agencies as to the desirability and appropriateness of formalizing NASA's Orbital Debris Mitigation Standard Practices, including the "25-year rule," and NASA Procedural Requirements for Limiting Orbital Debris as legal rules that could be applicable to U.S. non-NASA missions and private activities.**
- **<u>Finding</u>: The institutions and agreements that have been used to address issues related to orbital debris are primarily political, not legal, in nature. The success of those agreements will thus depend on a complex interplay of good faith; political will; and political, economic, and, sometimes, legal forces.**

Chapter 11: Issues External to NASA

- **<u>Recommendation</u>: NASA should continue to engage the international community to develop cooperation and political will regarding activities concerning orbital debris.**
- **<u>Recommendation</u>: NASA should assess the value of alternative data sets, such as participating in the not-for-profit Space Data Association, to determine how sharing operator ephemerides might improve the accuracy and efficiency of NASA's Conjunction Assessment Risk Analysis (CARA) by incorporating the best data possible in its CARA process.**
- **<u>Finding</u>: Debris removal activity that involves selecting and removing any given object—debris or otherwise—from space, crosses crucial national and international legal thresholds.**
- **<u>Recommendation</u>: NASA's meteoroid and orbital debris programs should engage the NASA General Counsel's Office and, through that office, the U.S. State Department regarding the legal requirements and diplomatic aspects of active debris removal.**

Chapter 12: Management and Organizational Issues

- <u>**Finding**</u>**: NASA's management structure has not kept pace with the expanding responsibilities of its MMOD programs. Consequently, the MMOD programs do not have a single management and budget point that can efficiently coordinate all of the current and planned activities and establish clear priorities.**
- <u>**Recommendation**</u>**: NASA should review the current management structure of its MMOD programs in order to achieve better coordination, provide improved central decision making, and establish a framework for setting priorities. This framework should include a major interface with Congress, other federal and state agencies, and the public.**
- <u>**Finding**</u>**: NASA's MMOD researchers do not consistently communicate the results of their work to the scientific community, with the result that users have less understanding regarding the underlying assumptions and intricacies of NASA's codes and models.**

Chapter 12: Management and Organizational Issues

- **Recommendation**: NASA should encourage its MMOD researchers to more fully communicate the results of their work and their development activities, such as in appropriate peer-reviewed publications when possible, so that users of NASA's codes and models gain a greater appreciation for and more clearly understand the underlying assumptions and intricacies of NASA's codes and models.
- **Finding**: Nearly all of NASA's MMOD programs are only one person deep in staffing. This shortage of staffing makes the programs highly vulnerable to budget reductions or changes in personnel. Further reductions in real budgetary support over the coming years could threaten the viability and scope of ongoing MMOD programs.
- **Recommendation**: NASA should develop a formal strategic plan that provides the basis for prioritizing the allocation of funds and effort over various MMOD program needs. Among the potential research needs and management issues to be considered is the selection listed in Box S.1. The strategic plan should consider short- and long-term objectives, a schedule of benchmark achievements to be accomplished, and priorities among them. Stakeholders should be engaged to help develop and review this plan. Finally, the MMOD strategic plan should be revised and updated at regular intervals.

Chapter 13: Preparing for the Future

- **<u>Finding</u>: The long-lived problem of growth in the amount of orbital debris population as a result of debris self-collision and propagation requires that NASA take a long-term perspective to safeguard the space environment for future generations.**
- **<u>Finding</u>: Although the meteoroid and orbital debris environment may be manageable at present, debris avoidance, mitigation, surveillance, tracking, and response all require money. At present, these costs usually come in the form of additional spacecraft mass and fuel and in the maintenance of debris surveillance systems. Such costs are usually absorbed in the budgets for space mission design, operations, and, in the case of commercial activities, insurance premiums. In the absence of appropriate meteoroid and orbital debris management to deal with the issue, these costs may grow over time. Although they can serve to highlight the importance of NASA's debris measurement and monitoring activities, at present these costs are not routinely measured and reported.**
- **<u>Finding</u>: The cost of replacing spacecraft has been used as a measure of the economic harm of a catastrophic debris impact but may underestimate the full cost of harm for two reasons: (1) actual replacement may be difficult because of funding, launch window limitations, or other constraints; and (2) replacement cost, insurance premiums, and other measures of the cost incurred to protect a spacecraft understate the full cost to society as a whole if that spacecraft, damaged by a meteoroid or orbital debris, itself generates debris that then creates potential harm to other spacecraft.**

Chapter 13: Preparing for the Future

- **Recommendation: NASA should lead public discussion of the space debris problem to emphasize debris as a long-term concern for society that must continue to be addressed today. Necessary steps include improvements in long-term modeling, better measurements, more regular updates of the debris environmental models, and other actions to better characterize the long-term evolution of the debris environment.**
- **Recommendation: NASA should join with other agencies to develop and provide more explicit information about the costs of debris avoidance, mitigation, surveillance, and response. These costs should be inventoried and monitored over time to provide critical information for measuring and monitoring the economic impact of the meteoroid and orbital debris problem, signaling when mitigation guidelines may need revision, and helping to evaluate investments in technology for active debris removal.**