Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

EUROPEAN ACTIVITIES ON SPACE DEBRIS

W. Flury
Mission Analysis Section, ESA/ESOC
Darmstadt, Germany

ABSTRACT

In this paper past and current European efforts in the space debris field are described. In 1986 ESA's Space Debris Working Group (SDWG) was created with the mandate to assess the various issues of space debris. Based on the findings and conclusions of the SDWG, the Council of ESA has defined in 1989 the Agency's objectives in the field of space debris and approved a plan of activities. First measures to reduce the growth of the number of debris have been implemented and a space debris research programme has been initiated. International cooperation was proceeding at European level between member states and worldwide between ESA and other space agencies.

1. INTRODUCTION

ESA's early concerns in the domain of space debris were the uncontrolled reentry of spacecraft (e.g. the nuclear-powered spacecraft Kosmos 954, Kosmos 1402, and Skylab) and collision risk in the geostationary orbit (Ref.1). In 1985 a workshop was held at the European Space Operations Centre, ESOC, to discuss the problem of uncontrolled reentry of risk objects (Ref.2).

Anticipating, however, the decision to embark on manned programmes (Ref.3), ESA concluded that a comprehensive analysis of space debris hazards was required. For this purpose, the Director General of ESA created in 1986 the Space Debris Working Group (SDWG) with the mandate to assess the various issues of space debris and recommend actions. The findings and conclusions of the SDWG were published in ESA's *Report on Space Debris*, ESA-SP 1109 (Ref.4).

The basic hazard caused by debris is damage through collision. As all objects orbiting around the Earth move with high velocity, regardless of their orbit, collisions with particles in the millimeter to centimeter range can have rather damaging effects. In addition, collisions are a source for additional debris. Once a critical object density is reached, an uncontrolled growth of space debris could result from collisions (chain reaction, Kessler effect, Ref.5).

The potential problems of space debris have been recognized and described at several occasions. An example is the *Report on Orbital Debris* by the U.S. Interagency Group (Space) for the National Security Council (Ref.6). Space debris is an international problem. It is regularly discussed at symposia organized by the International Astronautical Federation (IAF), the International Academy of Astronautics (IAA) and the Committee on Space Research of the International Council of Scientific Unions (COSPAR), Ref.7. Regulatory and legal aspects are addressed by the International Institute of Space Law (IISL). The United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) with its two sub-committees is examining scientific, technical and legal aspects.

2. ESA ACTIVITIES 1989 - 1992

Having received from the Space Debris Working Group the comprehensive analysis and recommendations it sought, ESA's Council adopted in 1989 a policy on space debris with the objectives

- to minimize the creation of space debris
- to reduce the risk for manned and unmanned space flight
- to reduce the risk on ground due to re-entry of space objects
- to acquire data on the debris population as needed for the execution of its programmes.
- to study the legal aspects of space debris

and approved a plan of activities.

The ESA Space Debris Advisory Group, composed of experts from ESA member states has been created, to advise the Agency in all matters of space debris. Chairman of SDAG is Prof. Rex, TU Braunschweig.

While debris-related work is carried out at the various ESA establishments, ESOC has been entrusted with the coordination of all ESA activities on space debris.

A main element of the current activities is the Space Debris Research Programme. Its purpose is to study critical areas and carry out preparations for future programmes. It covers three main areas: a) knowledge of the terrestrial particulate environment, b) the risk posed by space debris and c) protective and preventive measures.

- Environment. Research activities address the methods to measure the debris environment (ground-based and space-based sensors, in situ measurements with debris detectors), analysis of material and spacecraft surfaces exposed to the space environment, the mathematical modelling of the meteoroid and debris environment, and the long-term evolution of the debris population.
- Risk analysis. Assessments are carried out of the risk posed by space debris to spacecraft in low Earth orbit and in the geostationary ring.
- Protective and preventive measures. For some projects, mainly in the area of manned space flight, the increasing hazard from space debris calls for the implementation of protective measures such as shielding or collision avoidance. Hypervelocity impacts and their effects on spacecraft structures are investigated. Another area of research is debris minimization and prevention through appropriate design and operation concepts.

3. ACHIEVEMENTS OF PHASE 1 (1989-1992)

The major activities carried out during this first phase are summarized below. Detailed information (including national activities (Ref.8)) can be extracted from the references.

3.1 Knowledge of the environment

The DISCOS data base. The Agency has established at ESOC through a contract with the Unit for Space Science of the University of Kent at Canterbury the DISCOS space debris data base for its own use and entities in the member states (Ref.9,10). It supplies information on the currently catalogued objects and is a basis for risk assessments and understanding of the evolution of the environment. DISCOS contains as major elements the NASA Two-Line Elements which are regularly updated, the NASA Satellite Situation Report, the RAE Table of Earth Satellites and information on satellite fragmentation. The RAE Table of Satellites, is a chronological list of all satellites launched since 1957, giving the name and international designation of each satellite and its launcher, with the date of launch, lifetime, orbital parameters and physical parameters of the satellite and upper stage (Ref.11).

Sensors and facilities for space debris observation and tracking. Europe has no system for space surveillance, i.e. the systematic monitoring of all space objects. However, some facilities exist for the tracking of selected objects.

- Radar of FGAN (Research Establishment for Applied Science) in Wachtberg-Werthhoven, Germany. With this powerful radar, which operates in L-band and Ku-band and providing narrow-band as well as high resolution radar data, space objects can be tracked over large areas of Europe (Refs.2,12,13). Research on the physical characteristics (radar-cross section, shape, mass, attitude) of space objects is carried out.
- Radar and optical stations in France. At the occasion of reentry of risk objects they provide data for reentry predictions.
- A survey on the use of optical and infrared sensors for the detection and tracking of space debris has been carried out by SIRA Ltd., Chislehurst (UK), Refs.14,15.

Analysis of IRAS data. The infrared astronomical satellite IRAS, launched in 1983 to perform a sky survey at wavelengths ranging from 8 to 120 μm, was operational during 10 months in a sun-synchronous orbit near 900 km altitude. The satellite was pointing radially away from the Earth and scanning the celestial sphere at a velocity of 3.85 arc minutes per second. The full unprocessed IRAS data have been analyzed by the Space Research Organisation of the Netherlands (SRON), Groningen, in order to characterize the infrared emission of debris objects and to extract a comprehensive set of debris sightings. The method to identify space debris signatures is based on the recognition of their track over the IRAS focal plane (Refs.16,17).

Space experiments for collection of cosmic dust and small-size debris. Europe has a long tradition in cosmic dust research. Already ESRO satellites carried dust experiments in Earth orbit, and recently, by GIOTTO to comet Halley, and in 1992 to comet Grigg-Skjellerup, Ulysses and Galileo. Several European institutes and research groups are involved in dust and debris experiments and analysis, e.g.

- University of Kent, Canterbury (Prof. Mc Donnell)
- MPI Heidelberg (Prof. Grün, Prof. Jessberger)
- ONERA, Toulouse (Dr. Mandeville)
- Technical University Munich (Prof. Igenbergs)
- University of Bremen (Dr. Iglseder)
- Space Science Department, ESTEC.

The return to Earth in January 1990 of NASA's Long Duration Exposure Facility (LDEF) has provided a wealth of information on the LEO particulate environment through specially designed experiments (Refs.18,19) and the record of impacts on surface material. The particular shape of LDEF and the controlled attitude throughout the 68 months in orbit allow to validate and improve models of debris and meteoroids. European dust and debris experiments on LDEF are FRECOPA (Mandeville et al.) and the Multiple-foil Microabrasion Package (University of Kent, Canterbury). Furthermore, about 18 sqm of exposed thermal blankets of the Ultra Heavy Cosmic Ray Nuclei Experiment (UHCRE, Dublin Institute for Advanced Studies and Space Science Department, ESTEC) are available for impact analysis and investigations on chemical composition of dust residues.

EURECA, the European Retrievable Carrier, was launched in July 1992 in a circular orbit near 510 km altitude at 28 ° inclination and retrieved by the Space Shuttle in June 1993. It carried the Timeband Capture Cell Experiment (TICCE), an instrument designed for the study of microparticle population of man-made and natural origin (dust grains from cometary, asteroidal and other sources).

Modelling of the debris environment. A reference debris and meteoroid model is established based on the cataloged population, record of fragmentations, mathematical modeling of fragmentations and the results of LDEF impact analyses (Refs.20,21).

At the Technical University of Braunschweig (Germany) studies are carried out addressing the modelling of the space debris population, debris collision warning and avoidance, removal of space debris from orbit (Ref.22) and other aspects of the debris problem. In particular, the question of the long-term evolution of the debris population is investigated (Ref.23). Similar questions are also addressed by a research group in Pisa (Ref.24). These analyses show, that under certain assumptions, debris generated by collisions in space can initiate a self-sustained chain reaction, which could lead to a strong increase of the number of man-made objects in space. Analyses indicate that in some densely populated regions the critical density is only about 2 to 3 times the current population.

3.2 Risk analysis.

Analysis tools for the impact analysis, evaluation of collision probability and risk assessment for meteoroids and space debris are developed further. A 3D geometrical tool for impact risk assessment within the ESABASE framework has been completed (Refs.25,26). Based on existing meteoroid and debris models, the particulate environment near a space vehicle can be modeled. Impact probabilities are determined and damage assessment carried out based on analytical damage formulations.

Colocation in the geostationary orbit means assigning to several satellites the same longitude slot. For example at 19 deg W Olympus-1, TDF-1, TDF-2 and TVSAT-2 have all been assigned a common window of $\pm 0.1°$. Simulations at DLR, Oberpfaffenhofen, of the motion of 4 colocated satellites with uncoordinated station-keeping have shown that the expected time between close encounters of 50 m or less is 0.6 years (Ref.27). As this is clearly unacceptable, optimized orbit control schemes have been devised. An interesting approach is based on using slightly different orbital parameters for the colocated satellites. With separation by different eccentricity and inclination vectors, the collision probability can be drastically reduced. The penalty is a slightly higher fuel consumption.

3.3 Debris prevention and protection

Geostationary orbit. Current issues in this increasingly used orbit are reorbiting, colocation, and risk analysis (Ref.28). ESOC issues regularly a list of all known geostationary and near-geostationary objects (Ref.29).

ESA spacecraft in geostationary orbit must be reorbited into a graveyard orbit at end-of-life. In 1984 GEOS-2 was boosted into a disposal orbit 230 km above the geostationary orbit. In 1991 the satellites OTS-2 and Meteosat-2 were transferred to orbits 320 km and 335 km above the geostationary orbit.

As regards colocation, independent orbit control will lead to a high probability for collision or close encounter. Special station-keeping strategies can be identified to maintain physical separation, at the expense of a slightly increased fuel consumption (Ref.30).

Shielding and impact analysis. Preparation for manned missions. Investigations for debris and meteoroid protection are in progress. A summary of the spacecraft shielding activities undertaken under the technology programme of ESA is provided in Refs.31,32. They include various areas, such as hypervelocity impact tests with light gas guns, mathematical modeling of impacts (hydrocodes) and damage assessment, material research and optimized shield structure. As light gas guns are limited in their capabilities for reaching high velocities (maximum is near 10 km/s), hydrocodes are used for higher velocities. A promising method to reach higher impact velocities is based on shaped charges (Ref.33). Limitations of this approach are the restricted impactor shape and small mass.

Several entities are involved in the various aspects of debris and meteoroid protection and spacecraft shielding, and damage assessment and localisation, e.g.

- MBB-ERNO, Bremen.
- Aeritalia, Torino.
- Ernst-Mach Institut, Freiburg.
- Battelle Institut, Frankfurt.
- Engineering Systems International (ESI), Paris.

- Det Norske Veritas, Oslo.

Passivation of Ariane upper stage. As regards launches of Ariane 4 into low altitude circular orbits, the residual fuel in the upper stage is vented. This procedure was applied in case of SPOT-2, ERS-1, and Topex/Poseidon. For the Ariane 5 launcher (first launch 1995) propellant venting or deorbiting of the upper stage L9 are under consideration.

Debris prevention. A study has been carried out to analyze the debris production process on a representative selection of space systems and to recommend technical measures for the prevention and reduction of space debris (Ref.34). The outcome of this study is used for the definition of clauses in ESA's PSS (Procedures, Standards, Specifications) documents concerned with debris preventative measures.

Re-entry of risk objects. Recent examples of re-entry of risk objects are Kosmos 1900 (Sept. 1988) and the Salyut-7/Kosmos-1686 complex (Feb. 1991). Mathematical methods and software tools have been improved to cope with this problem and provide re-entry warnings to the member states. In April 1991 an International Workshop was held at ESOC on the reentry of Salyut-7 (Ref.35).

3.4 Safety regulations

Within ESA safety regulations are in force which address the generation of space debris and the risk due to space debris falling on the Earth's surface. Formal specifications which are applicable to ESA space systems and associated equipment are contained in the PSS documents. In ESA PSS-01-40 Issue 2 (Ref.36), "System safety requirements for ESA space systems and associated equipment", space debris is addressed. Clause II-1.6.2 states: "Means shall be provided to prevent the hazardous descent of debris as the result of a launch vehicle launch abort, or the uncontrolled de-orbiting or orbital decay of spacecraft, or space system elements that are likely to survive re-entry". Clause II-1.6.4 is concerned with the creation of debris: "The creation of space debris in orbits that repeatedly intersect orbital paths used by space systems shall be avoided".

3.5 Legal aspects

ESA in observer status is participating in the sessions of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) which sometimes deliberates on space debris and space environment issues such as nuclear power sources.

Several European institutes are concerned with Space Law. The workshop "Environmental Aspects of Activities in Outer Space" was held in Cologne, May 17-19, 1988. It was attended by lawyers, scientists and engineers. This interdisciplinary meeting included presentations and discussions on technical, scientific and legal issues (Ref.37).

In 1989 the European Centre for Space Law (ECSL) was founded. The main purposes are: to exploit and complement efforts in the field of space law; to promote knowledge of and interest in space law; to identify areas of space-related activity in which regulation is appropriate. ECSL is supported by ESA.

3.6 Coordination and discussion with other space agencies.

Regular coordination meetings have been held with NASA since 1987. Preliminary discussions took place with organisations from Russia (earlier Soviet Union) and Japan.

4. PLANNED ESA ACTIVITIES 1993-1995

The Phase 1 activities have led to a clearer understanding of the space debris issue and to the implementation of a number of debris preventative measures.

Phase 2 will be concerned with the consolidation of the work performed in Phase 1 and will further advance the achievements as addressed in the sequel. An important element will be international cooperation, both on a European and worldwide level.

The main objectives during this phase are:

- improved understanding of debris environment and associated risks;
- further implementation of debris preventative and protective measures;
- coordination with national activities in member states;
- cooperation and discussion with other space agencies and organisations;
- preparing internationally accepted technical standards for debris control.

These objectives will be reached by a joint effort of ESA and its member states. An important factor will be the coordinated use of national facilities for space debris observation (radar, optical), hypervelocity impact tests, analysis of material returned from space and the identification of methods and approaches for debris reduction.

4.1 Knowledge of the Environment

The objective is to gain a more comprehensive knowledge of the space debris population in terms of size and spatial distribution. As Europe has only very limited own capabilities to observe objects in space, Europe relies strongly on the US surveillance system. Activities will therefore focus on:

- further upgrading of ESA's DISCOS debris database;
- improving European ground-based observation capabilities (radar, optical) through optimum use of national facilities (e.g. radar stations in France, Germany and United Kingdom) and ESA facilities (e.g. 1-Meter telescope to be installed for the ARTEMIS project).
- gaining information on the small-size debris population (micron to millimeter size) through analysis of material returned from space and dust experiments, e.g. EURECA and solar arrays of Hubble Space Telescope.
- preparing space-based observations with small aperture (10 cm) optical instruments in order to gain information on the mid-size debris population (1 to 50 cm).

4.2 Risk analysis

Tools for risk analysis (e.g. ESABASE/DEBRIS) need further upgrading and application to the Agency's programmes. This includes implementing improved debris and meteoroid models, new results in material response under impact, and advanced methods for risk assessment.

Also, standards need to be developed for the acceptability of risk caused by space debris for the different space vehicles.

4.3 Debris mitigation and protection

Fuel venting of the Ariane 4 third stage will be carried out routinely from flight 59 (V59) onwards regardless of the type of the target orbit. Debris mitigation measures for Ariane 5 will be further investigated.

The end-of-life disposition into a graveyard orbit of geostationary satellites will further be applied by the Agency. Further work will address the location of the disposal orbit, disposition of separated apogee-boost motors, and collocation. However, reorbiting can only be considered as an interim measure. Ultimately, removal from orbit will be required.

Upgrading of impact test facilities and numerical methods is necessary for realistic simulations of the space environment and its effect on space systems. Experimental tests and numerical simulations should cover a larger range of impact direction and velocity, pressure regime, and type of materials. Activities will therefore focus on:

- accelerators using shaped charges
- graded density impactors
- computer simulations
- hypervelocity impact on pressurized vessels
- advanced measurement techniques
- advanced shielding concepts.

Shielding and protection of manned vehicles will be continued to meet the safety requirements of the Agency.

ESA has since 1988, as part of the safety policy, a specific requirement for prevention of debris creation as defined in PSS-01-40. The PSS documents represent formal standards for space system design. They will be upgraded to reflect new results in the space debris field.

For debris reduction and control technical analysis is required in order to establish internationally agreed standards.

4.4 International cooperation

As space debris is a global problem which only can be solved by a joint effort, discussions and cooperation with other space agencies and related organizations will be further enhanced.

On the occasion of the First European Conference on Space Debris, the first multilateral meeting with representatives of NASA, the Russian Space Agency, Japan, and ESA has taken place in Darmstadt on April 2-3 1993. It was agreed to establish a Space Debris Coordination Committee which would regularly meet semi-annually and would be supported by technical working groups dedicated to four specific areas: i) measurements of the environment, ii) data base and environment modelling, iii) testing and shielding, iv) mitigation. Within the framework of this cooperation the four parties will exchange relevant technical information and experience related to space debris and will prepare common strategies to counter the space debris problem. In particular, the need was recognized to implement in extension to the DISCOS data base a common data base of the space debris environment which will be supported by the surveillance networks and observation facilities of all four participants.

In the absence of internationally agreed regulations and conventions on space debris mitigation and control, the aforementioned cooperation can be considered as a significant step toward a common approach on space debris control between four major space operators.

4.5 Regulatory and legal issues

International regulations addressing space debris are in preparation. For example, Working Party 4A of CCIR has approved recommendations concerning the environmental protection of the geostationary orbit. Nonetheless, international space law is not adequately addressing the space debris issue. In view of the recognized problem, ESA should therefore intensify its endeavors in close cooperation with member states toward reaching a common policy as starting point for regulations and international agreements.

5. CONCLUSION

In response to the objectives which ESA's Council formulated in the field of space debris, the Agency, in cooperation with the member states and other Space Agencies, has initiated a study programme and other technical activities with the aim to observe, register and analyze the distribution of space debris in the space environment, as well as to assess the risk involved for space missions. Debris protective techniques were tested and a number of debris preventative measures have been implemented, such as the reorbiting of geostationary satellites at the end of mission life time and the passivation of the Ariane third stage in low Earth orbit.

Space debris denotes a serious long-term hazard to manned and unmanned spaceflight. ESA's debris-related activities in Phase 1 have led to an increased awareness of the problem.

The activities proposed for the period 1993-95 constitute a minimum programme of work to consolidate earlier activities and to gain an improved understanding of the critical issues of this growing hazard. The European debris data base DISCOS will be upgraded to a more comprehensive and accurate representation of the debris environment and work on debris preventative and protective techniques and measures will be further pursued.

International cooperation with the major space operators, such as NASA, the Russian Space Agency and Japan, will be strengthened by the institution of the Space Debris Coordination Committee, which will provide an effective forum for exchange of technical information and methods in support of a common approach to space debris control and preventative measures. This cooperation is of paramount importance to safeguard the space environment and keep the risk to spaceflight within tolerable levels.

6. REFERENCES

1. Hechler M., Van der Ha J. C., Probability of collision in the geostationary ring, *J. of Spacecraft and Rockets* , Vol.18, No.4, 1980.

2. Re-entry of Space Debris , ESA SP-246, Proc. ESA Workshop, ESOC, Darmstadt, 1985.

3. Roth E.A., Space Debris - A Hazard for the Space Station ?, *ESA Journal* , Vol.44, 63-65, 1985.

4. SPACE DEBRIS. The Report of the ESA Space Debris Working Group, ESA-SP 1109, 1988.

5. Kessler D.J., Orbital Debris Environment for Spacecraft in Low Earth Orbit, *J. of Spacecraft and Rockets* , Vol.28, No.3, 1991.

6. Report On Orbital Debris by the Interagency Group (SPACE) for National Security Council, Washington D.C., 1989.

7. Flury W. (Ed.), Space Debris , Proc. COSPAR/IAF Topical Meeting on Space Debris, World Space Congress, 1992, Washington D.C., USA, *Adv. Space Res.*, Vol.13, No.8, Pergamon Press, 1993.

8. Frenzel D., Heumann H., Alwes D., Schrogl K.-U. (Ed.), Stand der Space Debris - Forschung in Deutschland und internationale Regulierungsfragen, DARA, Bonn, 1992.

9. Klinkrad H., DISCOS. ESA's Database and Information System Characterising Objects in Space, XXVIII COSPAR, The Hague, 1990.

10. Space Debris Database DISCOS, University of Kent, Canterbury, ESA Report CR(P) 3266, 1990.

11. King-Hele D.G. et al, The R.A.E. Table of Earth Satellites 1957-1990 , Royal Aerospace Establishment, Farnborough, 1990.

12. Mehrholz D., Radar measurements of debris size, AIAA 90-1344, AIAA/NASA/DOD Orbital Debris Conference, Baltimore, 1990.

13. Mehrholz D., Space object observation with Radar, *Adv. Space Res.*, Vol.13, No.8, 33-42, 1993.

14. Lobb D.R. (Ed.), Study on optical sensors for space debris observation, ESA CR(P) 3606, 1992.

15. Lobb D.R. et al., Development of concepts for detection and characterisation of debris in Earth orbit using passive optical instruments, *Adv. Space Res.*, Vol.13, No.8, 59-63, 1993.

16. Wesselius P. et al., Detecting Orbital Debris Using IRAS, ESTEC Contract No. 8736, 1992.

17. Wesselius P. et al., Space debris observed by IRAS, *Adv. Space Res.*, Vol.13, No.8, 49-57, 1993.

18. McDonnell J.A.M. et al., The near Earth space impact environment - an LDEF overview, *Adv. Space Res.*, Vol.13, No.8, 87-101, 1993.

19. McDonnell J.A.M. (Ed.), Hypervelocity Impacts in Space , Proc. Workshop on Hypervelocity Impacts in Space, University of Kent, Canterbury, 1992.

20. Klinkrad H., Jehn R., The Space Debris Environment of the Earth, *ESA Journal* , Vol.16, No.1, 1-11, 1992.

21. Jehn R., Dispersion of debris clouds from on-orbit fragmentation events, IAF-90-565, 41st IAF Congress, Dresden, 1990.

22. Eichler P., Bade A., Removal of debris from orbit, AIAA 90-1367, AIAA/NASA/DOD Orbital Debris Conference, Baltimore, 1990.

23. Eichler P., Rex D., Chain reaction of debris generation by collisions in space - a final threat to spaceflight ?, IAF-89-628, 40th IAF Congress, 1989.

24. Cordelli A. et al., Future collisional evolution of Earth-orbiting debris, *Adv. Space Res.*, Vol.13, No.8, 215-219, 1993.

25. Borde J., Drolshagen G., Centeno H., 3-D geometrical meteoroid/debris analysis tool for impact risk analysis, Proc. ESA Workshop on Space Environment Analysis, ESA WPP-23, 1990.

26. Development of Meteoroid/Debris Analysis Tool, Final Report, ESTEC Contract No. 8371/89/NL/JG, Matra Espace, 1991.

27. Eckstein M.C. et al., Colocation Strategy and Collision Avoidance for the Geostationary Orbit at 19 Degrees West, Symp. Space Dynamics, Toulouse, 1989.

28. Flury W., Collision probability and spacecraft disposition in the geostationary orbit, XXVIII COSPAR, The Hague, 1990.

29. Janin G., Log of Objects Near the Geostationary Ring, Issue 11, ESOC, 1993.

30. Station-Keeping Strategies for Colocated Satellites, ESTEC Contract No. 9297/91/NL/PM, MBB-ERNO, 1992.

31. Lambert M., Shielding against orbital debris - a challenging problem, Proc. ESA Symposium on Space applications of advanced structural materials, Noordwijk, The Netherlands, ESA SP-303, 319-328, 1990.

32. Lambert M., Shielding against natural and man-made debris: a challenging problem, *ESA Journal* , Vol.17, No.1, 31-42, 1993.

33. Feasibility of high performance impact test facilities to simulate orbital debris, ESTEC Contract No. 9239/90, Battelle Europe, 1992.

34. Safe Disposal of Orbiting Systems and Spacecraft - Including the Prevention of Debris, ESA Contract No. 9024/90/NL/PM(SC), 1992.

35. Re-entry of Salyut-7/Kosmos-1686 , ESA SP-345, Proc. International Workshop, ESOC, Darmstadt, 1991.

36. System safety requirements for ESA space systems and associated equipment, ESA PSS-01-40 Issue 2, European Space Agency, Paris, France, 1988.

37. Böckstiegel K.H. (Ed.), Environmental Aspects of Activities in Outer Space , Proc. of an International Colloquium, Carl Heymanns Verlag Köln, 1990.