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Orbital Debris: A Chronology

David S. F. Portree
Joseph P. Loftus, Jr.

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Preface

This chronology is an updated version of NASA RP-1320, *Orbital Debris and Near-Earth Environmental Management: A Chronology*, December 1993. It provides an overview of the development, growing awareness, and management of orbital debris issues from 1961 to February 1, 1998. The chronology is, of course, not exhaustive. Every effort has been made, however, to at least touch upon all the important aspects of the history of orbital debris.

The expository sections (e.g., *Introduction - a Primer on the Problem*) cover specific aspects of orbital debris research, awareness building, and management which cannot be treated adequately in the chronology entries. They also provide overviews of complex event sequences which are difficult to track through the entries alone.

Included are entries describing important events in space history and space technology development which may not be directly related to orbital debris. One purpose for including these entries is to provide context for the orbital debris events. Another is to depict how human space activities have become increasingly complex, costly, and international in the past 4 decades. And at the same time, they have become increasingly vital to human civilization and increasingly vulnerable to the growing population of orbital debris.

This document was compiled through research using the Scientific and Technical Information Center at NASA's Johnson Space Center (JSC) in Houston, Texas. In addition, David S. F. Portree conducted approximately 45 hours of interviews with key players in the history of orbital debris. Joseph P. Loftus, Jr., is co-author, yet was interviewed in the same manner as the other key players. To adequately attribute his information and interpretations, his interviews are included in the citations.

The chronology makes no attempt to list all of the more than 150 known satellite breakups occurring in the period it covers. Only significant or illustrative breakup events are included. Other breakups are listed in Appendix 2. The number of satellites (artificial objects – operational spacecraft are a subset) in Earth orbit and the number of launches that reached Earth orbit or beyond are given with the heading for each year in order to suggest the growing magnitude of humanity's impact on the near-Earth environment. These numbers were derived by the NASA Orbital Debris Program at NASA JSC from the USSPACECOM catalog.

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The authors wish to thank the following players in the history of orbital debris, without whose assistance this chronology would not have been possible.

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Special thanks go to Nicholas L. Johnson, Donald J. Kessler, and Andrew E. Potter. Any errors remain the responsibility of the authors.

The individuals named above are those available for interview or who otherwise contributed to this book, but are, of course, no more than a tiny fraction of the number of persons making significant contributions to orbital debris work in the past 4 decades. Many more are named in the chronology; regretfully, however, it was not possible to include everyone who has made a contribution. The authors hope that this chronology will, by its very publication, serve to acknowledge all individuals around the world who have contributed to the present level of orbital debris knowledge.

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Acronyms and Abbreviations

AEDC	Arnold Engineering Development Center
AFB	Air Force Base
AFSPACECOM	Air Force Space Command
AIAA	American Institute of Aeronautics and Astronautics
AMOS	Air Force Maui Optical Site
ATDA	Augmented Target Docking Adapter
ARSAT	Art Satellite
ASAT	anti-satellite
ASI	Agenzia Spatiale Italiana
ASTP	Apollo-Soyuz Test Project
BNSC	British National Space Center
Cameo	Chemically Active Material Into Orbit
CCD	Charge-Coupled Device
CCIR	International Radio Consultative Committee
CDR	Critical Design Review
CDT	CCD Debris Telescope
CIS	Commonwealth of Independent States
cm	centimeter
CNES	Centre National d'Etudes Spatiales
CNSA	China National Space Administration
COBE	Cosmic Background Explorer
COLA	Collision on-orbit Avoidance
COMBO	Computation of Misses Between Orbits
COPUOS	Committee on the Peaceful Uses of Outer Space
COSPAR	Committee for Space Research
CP	Conference Publication
CRL	Communications Research Laboratory
CRS	Congressional Research Service
CSM	Command and Service Module
DARA	Deutsche Agentur für Raumfahrtangelegenheiten
DBS	Direct Broadcast Satellite
DECR	Debris Environment Characterization Radar
deg	degree
dia	diameter
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DTO	Development Test Objective
ECS	Experimental Communications Satellite
EDO	Extended Duration Orbiter
ELV	Expendable Launch Vehicle
EEO	Environmental Effects Office
EORSAT	ELINT Ocean Reconnaissance Satellite
ERS	European Remote Sensing
ESA	European Space Agency
ESEF	European Space Exposure Facility
ESOC	European Space Operations Center
ESTEC	European Space Technology Center
ETS	Experimental Telescope System

Eureca	European Retrievable Carrier
EVA	extravehicular activity
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FGAN	German orbital debris radar
FIDO	Flight Dynamics Officer
FY	fiscal year
GAO	Government Accounting Office
GAS	Get-Away Special
GBR-X	Ground-Based Radar-Experimental
GEO	geosynchronous earth orbit
GEOS	Geodynamics Experimental Ocean Satellite
GEODSS	Ground-based Electro-Optical Deep Space Surveillance
GSFC	Goddard Space Flight Center
HAPS	Hydrazine Auxiliary Propulsion System
HAX	Haystack Auxiliary
HIT-F	Hypervelocity Impact Test Facility
HIT-F	Hypervelocity Impact Technology Facility
HST	Hubble Space Telescope
IAA	International Academy of Astronautics
IADC	Inter-Agency Space Debris Coordination Committee
IAF	International Astronautical Federation
IAU	International Astronomical Union
IfRR	Institüt für Raumflugtechnik und Reaktortechnik
IG	Interagency Group
IKI	Institute for Space Research
INASAN	Institute for Astronomy
IRAS	Infrared Astronomy Satellite
ISAS	Institute of Space and Astronautical Sciences
ISRO	Indian Space Research Organization
ISS	International Space Station
ITU	International Telecommunications Union
IUS	inertial upper stage
JEM	Japanese Experiment Module
JGR	*Journal of Geophysical Research*
JPL	Jet Propulsion Laboratory
JSASS	Japan Society for Aeronautical and Space Sciences
JSC	Johnson Space Center
K	Kelvin
kg	kilograms
km	kilometers
LaRC	Langley Research Center
LDEF	Long Duration Exposure Facility
LEO	low Earth orbit
LK	Soviet Lunar Module
LM	Lunar Module
LMT	Liquid Mirror Telescope
m	meters
M	“Modified” (Progress M)

MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MCC	Mission Control Center
MDB	Mesh Double Bumper
MDSSC	McDonnell Douglas Space Systems Company
MEEP	Mir Environmental Effects Payload
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
mm	millimeter
MOA	Memorandum of Agreement
MOD	Mission Operations Directorate
MSC	Manned Spacecraft Center
MSFC	Marshall Space Flight Center
MSS	Multi-Shock Shield
MSTI	Miniature Seeker Technology Integration
MSX	Midcourse Space Experiment
MU	Middle and Upper atmosphere radar
NaK	Sodium-Potassium
NASDA	National Space Development Agency
NAVSPASUR	Naval Space Surveillance
NCSU	North Carolina State University
NEP	Nuclear Electric Propulsion
NMI	NASA Management Instruction
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
NPD	NASA Policy Directive
NRC	National Research Council
NSS	NASA Safety Standard
OCST	Office of Commercial Space Transportation
ODC	Orbital Debris Collector
ORDEM 96	Orbital Debris Engineering Model 1996
ODERACS	Orbital Debris Radar Calibration Spheres
OMS	Orbital Maneuvering System
OSF	Office of Space Flight
OTA	Office of Technology Assessment
PAGEOS	Passive Geodetic Earth-Orbiting Satellite
PARCS	Perimeter Acquisition Radar Characterization System
PIP	Program Implementation Plan
RA	right ascension
RCC	Reinforced Carbon-Carbon
RKA	Russian Space Agency
RORSAT	Radar Ocean Reconaissance Satellite
RTG	Radioisotope Thermal Generator
SAB	Scientific Advisory Board
SALT	Strategic Arms Limitation Treaty
SAO	Smithsonian Astrophysical Observatory
SARSAT	Search and Rescue Satellite
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SDRN	Soviet/Russian equivalent of U.S. TDRS satellite system
SEDS	Small Expendable Deployer System
SEM	Scanning Electron Microscope
SFU	Space Flyer Unit

SNAP	Systems for Nuclear Auxiliary Power
SPAS	Shuttle Payload Satellite
SPS	Solar Power Satellite
SRI	Southwest Research Institute
SRM	Solid Rocket Motor
SSF	Space Station Freedom
SSN	Space Surveillance Network
SSS	Space Surveillance System
S & T	Scientific and Technical
STS	Space Transportation System
T	Transport (Soyuz T, Soyuz TM)
TERESA	Tethered Remover Satellite
TDRS	Tracking and Data Relay Satellite
TiCCE	Timeband Capture Cell Experiment
TIM	Technical Interchange Meeting
TM	Technical Memorandum
TM	Transport Modified (Soyuz TM)
TOMS	Total Ozone Mapping Spectrometer
TSS-1R	Tethered Satellite System-1 Reflight
TUBS	Technische Universität Braunschweig
USML	United States Microgravity Laboratory
USSF	United States Space Foundation
USSPACECOM	United States Space Command
UT	Universal Time
WSTF	White Sands Test Facility

The Chronology

Introduction – A Primer on the Problem

Human space activities are largely concentrated in three Earth orbit altitude regions. These regions are Low Earth orbit (LEO), semi-synchronous orbit, and geosynchronous Earth orbit (GEO). Each offers particular advantages. LEO, 200-2000 km high, has the advantage of relative ease of access for the large masses required for piloted spacecraft. Close proximity to Earth makes LEO attractive for automated high-resolution-imaging spacecraft and high-signal-strength communications. LEO imaging spacecraft often use sun-synchronous orbits that ensure lighting conditions on Earth's surface are the same on each recurring orbit. Semi-synchronous orbits from 10,000 to 20,000 km high are important for navigation (the Global Positioning System constellation resides here), as well as communications. GEO - also called the Geostationary Arc - is 36,000 km high. The satellite telecommunications industry uses the Geostationary Arc, as do weather satellites. In GEO and LEO, human activities have become an important feature of the environment – at least in their effect on other human activities (this is best known for LEO – see fig. 1).

As a general rule, the higher above Earth's atmosphere a satellite orbits, the longer it will persist in orbit. At GEO altitude, atmospheric drag is unimportant. A GEO satellite is likely to orbit for millions of years. LEO is continually cleansed by atmospheric drag. Nevertheless, many LEO objects orbit for years, and most will orbit for centuries. The oldest artificial space object is the U.S. Vanguard 1 satellite. The 3968-by-650-km orbit it reached on March 17, 1958, ensured its longevity. The first satellite, the Soviet Union's Sputnik 1, decayed from its low orbit on January 1, 1958, less than 3 months after launch.

Of the approximately 25,000 orbiting artificial objects catalogued in the past 4 decades, about 8500 remain aloft. The Earth-orbital regions humans most use are so large that 8500 orbiting objects would constitute only the beginning of a crowding problem, if the numbers stopped there. But objects put into space seldom remain as they were on the ground. They shed lens caps, booster upper stages, nuts, bolts, paint chips, and bits of foil. Upper stages left in sun-synchronous orbits are subjected to continuous solar heating - this may induce overpressure and hasten corrosion, leading to structural failure in the stage propellant tank followed by a debris-producing rupture. In addition, solid rocket motors spray out billions of tiny aluminum particles; Space Shuttle orbiters dump waste water, which forms clouds of snowflakes; and spent upper stages and anti-satellite (ASAT) weapons explode. Most artificial space objects are too small to be detected from the ground using conventional satellite tracking techniques. The smallest of the more than 8500 objects in the USSPACECOM (formerly NORAD) catalog are about 10 cm across. There are estimated to be about 20 untrackable 1-cm objects and nearly 10,000 untrackable 1-mm objects for every trackable object. Artificial objects as small as 1 micron could number 100 trillion (fig. 2).

All of these objects have the potential to collide with other objects. The average speed of collision in LEO is about 10 km/second. At that speed, a 1-cm object massing a few grams packs the kinetic energy of a 250-kg object moving at 100 km/hour. In GEO speeds are slower and the volume of space is larger, but objects stay in orbit and pose a hazard longer.

When collisions occur more pieces are produced. When a paint chip the size of a grain of salt blasts a 3-mm pit in a Space Shuttle orbiter – not an uncommon occurrence – tiny fragments spray free and add to the orbital debris population. When a 1000-kg satellite is broken up by collision with a 10-cm object, millions of pieces will be produced. Many will be capable of causing new breakups.

Rate that a Catalogued Object is Expected to Pass within 100 Yards of an Orbiting Spacecraft

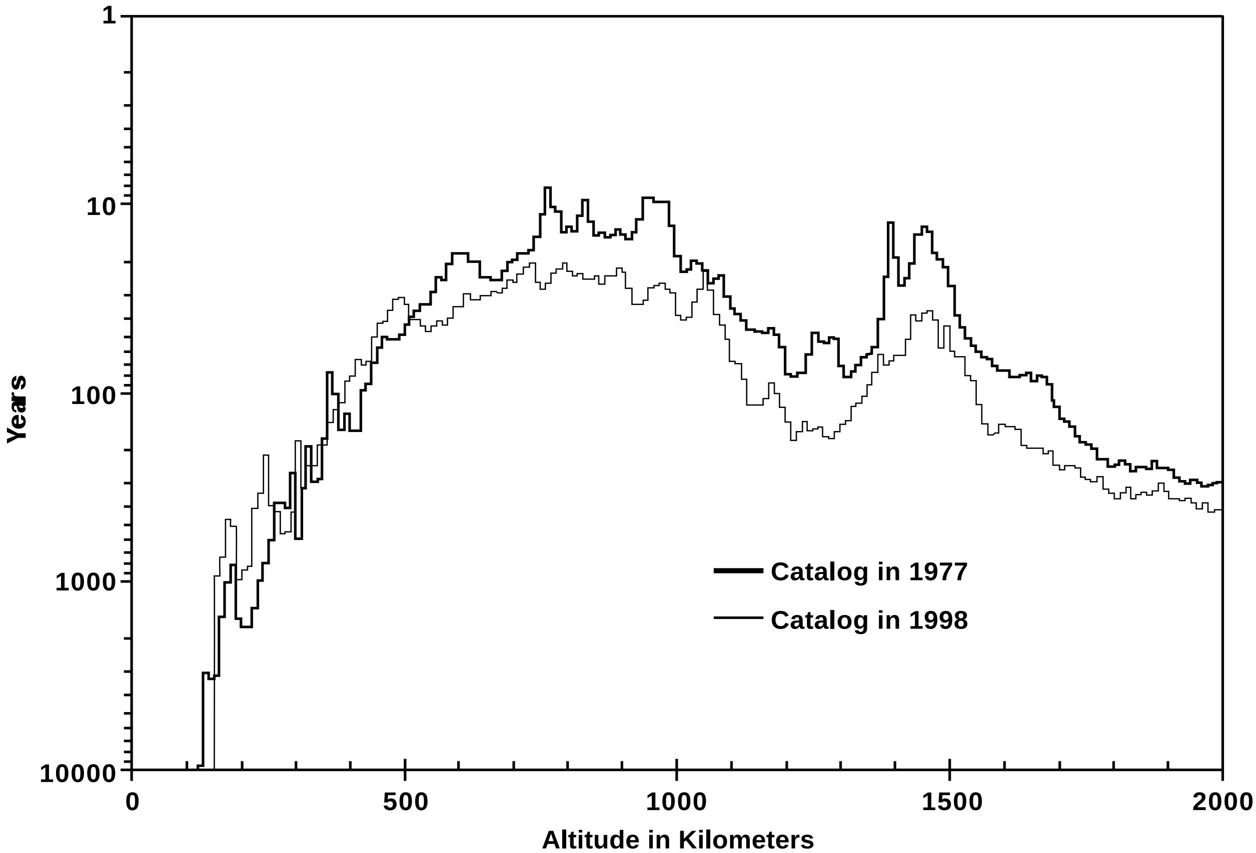

Figure 1.

In 1998 there were more than 8500 catalogued objects in Earth orbit. Finite probabilities exist that catalogued objects will pass near to or collide with a spacecraft. This chart shows how probabilities vary according to the altitude at which the spacecraft orbits. In certain orbital altitude regions – 700-1100 km and 1400-1600 km – there is an elevated risk of collision between a spacecraft and a catalogued object. However, the real risk comes not from catalogued objects, but from uncatalogued objects, which are vastly more numerous (see fig. 2).

Number of Objects in Low Earth Orbit as Estimated from Various Measurements

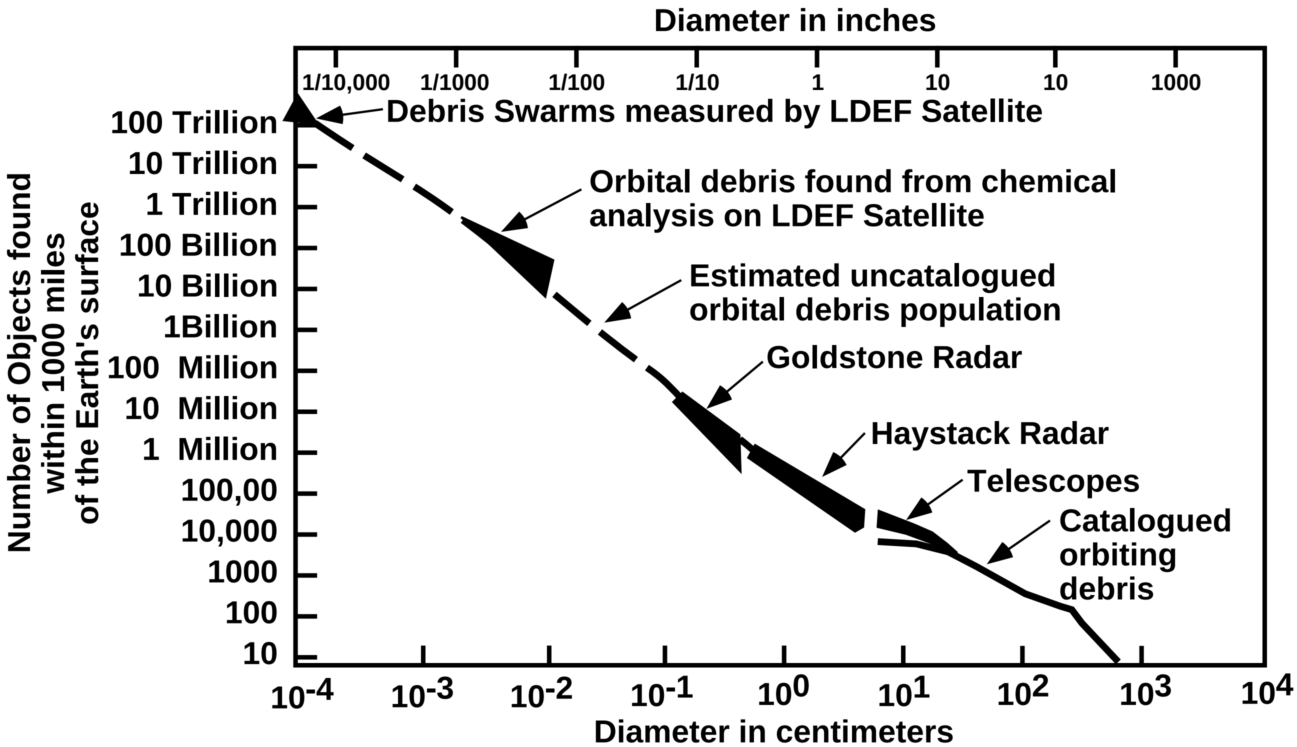

Figure 2.

The precise number of human-made objects in space is unknown. The present (1998) USSPACECOM catalog lists about 8500 objects. Use of detection methods more sensitive than those employed to create the catalog has produced dramatically higher estimates of the number of objects in Earth orbit. The smallest objects (paint chips, splinters of glass, and aluminum particles sprayed out by solid rocket motors) likely number 100 trillion. This chart is based on measurements which sample the environment and shows estimates of the number of objects in orbit of a given size and larger.

1961		
	End of year launches reaching Earth orbit or beyond (since 1957)	78
	End of year satellites (objects in orbit)	380

April 12

The Soviet Union launches Vostok 1. Its occupant, Yuri Gagarin, is the first human in space. His flight lasts about 90 minutes. Vostok 1 is a small target for artificial space objects, which, of course, are few at this time. It is approximately 4 m long and has a mass of 4725 kg.

June 28

Three-and-a-half years after the first artificial satellite, Sputnik 1, reaches orbit, the First Aerospace Control Squadron of the U.S. Air Force uses diverse radar and optical instruments to catalog 115 Earth-orbiting satellites. The instruments include NORAD's Baker-Nunn Schmidt cameras and the NAVSPASUR (Naval Space Surveillance System) radars headquartered at Dahlgren, Virginia.

June 29

Two hours after separating from the U.S. Transit 4-A satellite, its Able Star upper stage becomes the first known artificial object to break up unintentionally in space. The cause of the explosion is unknown. The event produces at least 294 trackable pieces, more than tripling the number of known satellites of Earth. Writing in 1966, satellite watcher Desmond King-Hele called this the first of the "real population explosions" in space. He said, "these bits and pieces. . . are a real curse. . . especially since most of the fragments will remain in orbit for a hundred years or more. By then the scrap metal may have cost more to track than the rocket cost to construct." Of the pieces produced, about 200 were still being tracked in orbit in 1998, more than 30 years after the breakup that created them.

Desmond King-Hele, *Observing Earth Satellites*,
St. Martin's Press, New York, 1966.

July

Project Moonwatch observers in Sacramento, California, observe 54 fragments of the Transit 4-A upper stage. Project Moonwatch was organized in 1957 by Fred Whipple of the Smithsonian Astrophysical Observatory (SAO). During its 18 years of operation (1957-1975), teams of amateur astronomers around the world track satellites optically and report their observations to the SAO. Some observers log thousands of satellite sightings.

Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper).

October 21

The U.S. Air Force launches the Midas 4 satellite on what is primarily a military surveillance mission. The satellite also deploys a spinning 35-kg canister into orbit at 3220 km in support of Project West Ford. The canister holds 350 million hair-like copper dipole antennas, the West Ford Needles. They are meant to scatter along Midas 4's orbit, forming an 8 km wide, 40-km deep belt around the Earth. The dipole belt will serve as a passive radio reflector for military communications. Information about the experiment released before launch raised protests from optical and radio astronomers. The Space Science Board of the National Academy of Sciences countered by describing how, in June 1960, it concluded that releasing the dipoles would "not harm any branch of science." A statement of U.S. government policy on

Project West Ford by Dr. Jerome B. Wiesner, Special Assistant to the President for Science and Technology, reinforced the Board view. The Board invites optical and radio astronomers to help study the effects of the dipole release. It maintains that the belt will be nearly undetectable, even to astronomers seeking it, and short-lived. These assertions are not tested, however, because the dipoles do not leave their canister.

"Project West Ford," *Spaceflight*, January 1962, pp. 24-25; Patrick Moore, "Communications on the Moon," *Spaceflight*, July 1963, p. 122; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 205.

1962

End of year launches reaching Earth orbit or beyond (since 1957)	150
End of year satellites (objects in orbit)	437

February 20 John Glenn becomes the first American in LEO. His Mercury capsule, *Friendship 7*, orbits Earth three times. Like Vostok, its Soviet counterpart, it presents a small target to space objects. *Friendship 7* is about 3 m long and 2 m in diameter. Three more orbital flights follow in the Mercury program. The last and longest is Gordon Cooper's 22-orbit flight of May 15-16, 1963. It lasts 34 hours, 20 minutes.

October 24 The Soviet Union launches Sputnik 29. On October 29 its SL-6 booster upper stage explodes, producing 24 trackable debris pieces. None remain in orbit.

1963

End of year launches reaching Earth orbit or beyond (since 1957)	205
End of year satellites (objects in orbit)	685

February 11 Ernest W. Peterkin, Operational Research Branch, U.S. Naval Research Laboratory, publishes the first of two memoranda on satellite collisions. Titled "Some Characteristics of the Artificial Earth Satellite Population," it predicts that the catalogued population will grow by 318 objects per year. This approximates the actual annual growth rate for catalogued objects up to the mid-1980s, uncorrected for the effects of solar activity.

Orbital Debris Monitor, Vol. 4, No. 3, July 1, 1991.

February 14 Peterkin's second memorandum is called "Implications of Artificial Satellite Population Growth for Long Range Naval Planning." He describes several ways in which a large satellite population could interfere with future naval operations. It might clutter space, making surveillance of surface targets difficult; interfere with future ASAT operations by creating a confusingly large number of targets; create decoy cover for fleet-launched ballistic missiles; and overload missile early warning systems.

Ibid.

May 9

The U.S. Air Force launches Midas 6. In spite of protests from astronomers, part of its mission is to support a repeat of the Project West Ford experiment. This time the plan is to release about 400 million dipoles into orbit. The experiment is only a partial success, because the dipoles do not scatter properly. It produces approximately 150 trackable debris pieces, presumably clumps of dipoles. Of the trackable clumps, about 65 remained aloft on January 1, 1998. Project West Ford is not repeated, in part because of the success of the active communications relay satellite Telstar 1, launched on July 10, 1962.

Patrick Moore, "Communications on the Moon," *Spaceflight*, July 1963, p. 122; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 205.

1964

End of year launches reaching Earth orbit or beyond (since 1957)	292
End of year satellites (objects in orbit)	825

April 21

The U.S. launches the Transit 5BN3 navigation satellite. The spacecraft is powered by the SNAP (Systems for Nuclear Auxiliary Power) 9 nuclear generator. It scatters radioactive materials over the Indian Ocean after its Scout launch vehicle fails. This is the worst space accident involving release of radioactive material until the uncontrolled reentry of the Cosmos 954 spacecraft in 1978.

Interavia Space Directory 1992-93, Andrew Wilson, editor, pp. 191-192.

August 19

Syncom 3 is the first successful satellite in GEO. It orbits Earth in approximately 24 hours, so from the ground it appears to remain almost stationary above the equatorial Pacific Ocean. The satellite acts as an antenna atop a tower reaching a tenth of the way to the Moon, relaying television from the Tokyo Olympics to half the Earth. The USSPACECOM catalog contains no current elements for this satellite. It probably remains in GEO, adrift. In the 3 decades since Syncom 3, hundreds of satellites have taken up residence in the economically valuable GEO region.

Arthur C. Clarke, *The Promise of Space*, Pyramid Books, 1968, p. 126.

October 28

Cosmos 50 is a reconnaissance satellite designed to return exposed film to the Soviet Union. After its recovery system fails, the Soviets command it to self-destruct so it will not land outside their national territory. None of the approximately 100 debris pieces produced remain in orbit.

1965

End of year launches reaching Earth orbit or beyond (since 1957)	404
End of year satellites (objects in orbit)	1626

March 18

The Soviet Union launches Voskhod 2, a modified version of the Vostok spacecraft. Voskhod 2 carries a deployable airlock. Alexei Leonov exits the spacecraft through this airlock to become the first person to conduct an extravehicular activity (EVA). Pavel Belyayev observes the 23-minute spacewalk from inside Voskhod 2.

March 23 Virgil Grissom and John Young enter space aboard the Gemini 3 spacecraft. Their flight, a test of basic Gemini systems, lasts nearly 5 hours. Gemini is the first manned spacecraft capable of extensive maneuvers, rendezvous and docking, and extended duration flights (up to 2 weeks). Each Gemini capsule is approximately 6 m long and 3 m in diameter.

June 28 Early Bird (Intelsat 1) triples trans-Atlantic telephone capacity by providing 240 telephone circuits. Early Bird is a drum 70 cm in diameter which weighs 68 kg at launch. The satellite is launched into a GEO slot at 325 deg east, over the Atlantic Ocean. The first commercial communications satellite, Early Bird is operated by the Intelsat Organization, a not-for-profit international corporation formed by 124 countries and signatories on August 20, 1964. The satellite operates for more than 3 years.

October 15 A U.S. Titan 3C transtage breaks up at an altitude of 739 km shortly after attaining orbit. This remains the worst known orbital debris event until 1986, with nearly 475 trackable debris pieces added to the near-Earth environment. About 50 trackable pieces remained in orbit on January 1, 1998. This is the only time a Titan transtage was left in LEO where its breakup could be confirmed by ground radars. About 30 have been left in GEO. At least one of those is believed to have broken up. However, USSPACECOM tracking limitations prevent confirmation.

Note, Donald J. Kessler to David S. F. Portree, August 2, 1993.

November 26 France becomes the third country (after the Soviet Union and the U.S.) to launch a satellite. Its A-1 (Asterix) satellite is launched into a 1758-km-by-528-km orbit at a 34-deg inclination by a Diamant launch vehicle.

1966

End of year launches reaching Earth orbit or beyond (since 1957)	522
End of year satellites (objects in orbit)	1695

March R. E. Dalton and J. N. Thilges of TRW Systems, Florida Operations, publish *Gemini GT-8 Orbital Collision Hazard Evaluation*, in which they state that "the logical admissibility of a collision between the spacecraft of the GT-8 mission and other orbiting objects is recognized to exist." They assume data supplied by NORAD for February 1-6, 1966, includes all Earth-orbiting satellites. Approach within 15 m is considered a collision. They determine that the probability is very small that the Gemini 8 capsule will be struck by orbital debris during the planned mission. A 313-km-by-145-km elliptical orbit yields a collision probability of 1.7×10^{-9}; a 242-km circular orbit yields a collision probability of 2.1×10^{-9}; and a 268-km circular orbit yields a collision probability of 2.3×10^{-9}.

R. E. Dalton and J. N. Thilges, *Gemini GT-8 Orbital Collision Hazard Evaluation*, TRW Systems, Florida Operations, March 1966.

March 16 Gemini 8 becomes the first spacecraft to dock with another vehicle in LEO. Shortly after they dock their spacecraft with the Augmented Target Docking Adapter (ATDA), Gemini 8 mission commander Neil Armstrong and pilot David Scott experience the first on-orbit emergency. A jammed maneuvering thruster forces them to undock from the ATDA and make an emergency reentry.

May 7

U.S. President Lyndon B. Johnson calls for an international treaty to regulate space exploration. He calls for the treaty to cover astronaut rescue and return to country of origin in the event of emergency landing, and liability for damage caused by space objects.

David S. F. Portree, *Thirty Years Together: A Chronology of U.S.-Soviet Space Cooperation* (NASA CR 185707), February 1993, p. 7.

May 9

The U.S. Ambassador to the U.N. presents the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS) with a draft of the Treaty on Principles Governing the Exploration and Use of Outer Space (the Outer Space Treaty). The draft version contains the stipulation that countries which cause damage through their space activities should be liable to make compensation for that damage.

Ibid.

July 20

A camera wielded by astronaut Michael Collins becomes an uncatalogued piece of orbital debris. He loses it while performing a spacewalk during the Gemini 10 mission. Before reentry, Collins and mission commander John Young open the hatches and discard unneeded equipment into orbit. None of this debris remains in orbit today; in fact, it probably reentered in a few days or weeks.

Michael Collins, *Carrying the Fire: An Astronaut's Journeys*, Giroux, Farrar, and Straus, 1974, pp. 235-236; James Grimwood, Barton Hacker, and Peter Vorzimmer, *Project Gemini: A Chronology* (NASA SP 4002), Washington, NASA Scientific and Technical Information Division, 1969, p. 251.

1967

End of year launches reaching Earth orbit or beyond (since 1957)	649
End of year satellites (objects in orbit)	1806

January 27

The U.N. opens the Outer Space Treaty to signature. The U.S., the Soviet Union, and more than 60 other nations sign. The final version of the treaty largely avoids the divisive issue of liability for damage caused by space activities.

David S. F. Portree, *Thirty Years Together: A Chronology of U.S.-Soviet Space Cooperation* (NASA CR 185707), February 1993, p. 8.

April 10

A NASA Manned Spacecraft Center (MSC) Flight Analysis Branch Internal Note espouses the prevailing view of the amount of orbital debris circling Earth, when it states that "the number of untrackable fragments which result from explosions of satellites in orbit and whose radar cross section areas are too small to be tracked by NORAD, constitutes an insignificant increase in the total number of objects in earth orbit and hence can be neglected in the calculation of collision probability." They calculate the probability of collision for an Apollo spacecraft to be only 3.68×10^{-5} for a 12-day mission and 11.16×10^{-4} for a 1-year stay in Earth orbit.

“Collision Probability of Apollo Spacecraft with Objects in Earth Orbit” (MSC IN 67-FM-44), April 10, 1967.

April 23-24 The Soviet Union launches Soyuz 1 with cosmonaut Vladimir Komarov aboard. Its mission is to dock with Soyuz 2. A cosmonaut from Soyuz 2 will then transfer by EVA to Soyuz 1 and return to the Soviet Union with Komarov. The mission is a rehearsal for several parts of the Soviet manned lunar landing mission plan. Soyuz 1 has power and guidance problems immediately after orbital insertion. The Soyuz 2 launch is postponed. During reentry the parachute system malfunctions and Komarov is killed.

October 10 The Outer Space Treaty comes into force.

1968

End of year launches reaching Earth orbit or beyond (since 1957)	768
End of year satellites (objects in orbit)	2011

October 11-22 Apollo 7 is the first flight of the U.S. Apollo Command and Service Module (CSM) spacecraft. Walter Cunningham, Donn Eisele, and Walter Schirra simulate docking and test the Apollo spacecraft systems in anticipation of lunar missions. The Apollo spacecraft is about 4 m in diameter and 10 m long.

October 20 Cosmos 249 is the first Soviet ASAT weapon. It is designed to maneuver close to a target in orbit and explode, pelting it with fragments. Cosmos 248 is the target. After reaching a 2135-km-by-538-km orbit at a 62.3 deg inclination, Cosmos 249 explodes, creating about 110 trackable pieces of debris. Of these, about half remained in orbit on January 1, 1998.

Nicholas L. Johnson, “Artificial Satellite Breakups (Part 2): Soviet Anti-Satellite Programme,” *Journal of the British Interplanetary Society*, Vol. 36, 1983, pp. 357-362; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 188.

November 1 The Cosmos 252 ASAT achieves a 2134-km-by-538-km orbit at a 62.3-deg inclination. It explodes when it passes near the Cosmos 248 target satellite. The intentional fragmentation produces 140 trackable debris pieces, of which about 50 remained in orbit on January 1, 1998.

Ibid.

December 21-27 The Apollo 8 spacecraft carries astronauts Frank Borman, William Anders, and James Lovell out of LEO. They complete 10 orbits of the Moon. This the first of nine times humans leave LEO.

December 27 The Soviet Union launches Cosmos 198 is the first of two Radar Ocean Reconnaissance Satellite (RORSAT) test vehicles. The satellite’s dummy nuclear reactor separates and boosts to 948-km-by-889-km storage orbit on December 29. Cosmos 198 is the first of 33 RORSATs launched up to March 1988.

Jos Heyman, *Spacecraft Tables*, Univelt, Inc., San Diego, 1992, p. 115. “Analysis of the Fragmentation Situation in the Neighborhood of Russian

Satellites with Nuclear Power Sources," A. I. Nzarenko, N. P. Morozov, E. I. Grinberg, N. L. Johnson, Z. N. Khutorovsky, and V. S. Yurasov, *Space Forum*, Vol. 1, Nos. 1-4, 1996, pp. 125-134.

1969

End of year launches reaching Earth orbit or beyond (since 1957)	878
End of year satellites (objects in orbit)	2390

July 16-24 On Apollo 11 Neil Armstrong and Edwin Aldrin land their Lunar Module (LM) *Eagle* on the Sea of Tranquility. Michael Collins remains in lunar orbit aboard CSM *Columbia.*

September 18 Intelsat 3-F1, launched this date, is the first satellite of the Intelsat 3 series. The eight satellites in the series each have 1200 telephone circuits and four TV channels. Whenever possible, at end-of-life they are boosted above GEO.

1970

End of year launches reaching Earth orbit or beyond (since 1957)	992
End of year satellites (objects in orbit)	2938

February 11 The Institute of Space and Aeronautical Science (ISAS) launches Osumi, the first satellite launched by Japan, atop a Lambda 4S-5 rocket. The test satellite transmits for 17 hours from a 5150-km-by-340-km orbit at a 31-deg inclination.

April 24 The Peoples' Republic of China launches its first satellite. A Long March 1 rocket places China 1 into a 2386-km-by-441-km orbit at a 68.4-deg inclination.

August Skynet 1B, a British military communications satellite, is launched on a U.S. Delta rocket. It is targeted for GEO, but its apogee kick motor fails. The failure may have created a long-lived debris cloud. It may periodically pass through GEO (no sensors exist to permit certainty). No orbital elements are maintained for Skynet 1B.

Nicholas L. Johnson, "The Crowded Sky: The Danger of Collisions in Geostationary Orbit," *Spaceflight*, Vol. 24, No. 12, December 1982, pp. 446-449.

October 3 Cosmos 367, launched this date, is the first RORSAT with a functioning nuclear reactor. The reactor successfully boosts into storage orbit after the satellite malfunctions a few hours after launch. Twenty-nine RORSAT reactors were in storage orbit in 1998.

"Analysis of the Fragmentation Situation in the Neighborhood of Russian Satellites with Nuclear Power Sources," A. I. Nzarenko, N. P. Morozov, E. I. Grinberg, N. L. Johnson, Z. N. Khutorovsky, and V. S. Yurasov, *Space Forum*, Vol. 1, Nos. 1-4, 1996, pp. 125-134.

October 20 In an MSC Internal Note titled "Collision Probabilities of Future Manned Missions with Objects in Earth Orbit," Michael E. Donahoo of the Flight Analysis Branch updates the April 10, 1967 calculations and applies them to

Skylab, a space station, and a large space base. Donahoo's calculations assume that the uncatalogued debris population is insignificant. He calculates the probability that a Skylab will be hit by orbital debris during an 8-month mission to be 2.27 x 10^{-4}. The probability for a space station is 1.083 x 10^{-2}. It is 1.179 x 10^{-2} for the large space base. He states that the large collision probabilities are "not surprising when the increased mission durations and larger vehicle sizes are considered."

Michael E. Donahoo, "Collision Probability of Future Manned Missions with Objects in Earth Orbit" (MSC IN 70-FM-168), October 20, 1970.

October 20-30 The Soviet Union's Cosmos 373 is launched on October 20 to serve as an ASAT target. The Cosmos 374 ASAT is launched on October 23. It explodes into more than 100 trackable pieces after two-and-a-half orbits, 4 hours after launch. Cosmos 375 intercepts Cosmos 373 on October 30 and explodes into more than 40 trackable pieces. Of the pieces produced in the two explosions, more than 40 percent remained in orbit on January 1, 1998.

Report on Orbital Debris, IG (Space), February, 1989; Nicholas L. Johnson, "Artificial Satellite Breakups (Part 2): Soviet Anti-Satellite Programme," *Journal of the British Interplanetary Society*, Vol. 36, 1983; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 188.

1971

End of year launches reaching Earth orbit or beyond (since 1957)	1112
End of year satellites (objects in orbit)	3208

Space Stations and Liability Issues, 1970-1973

By 1970, NASA had well-advanced plans for large space stations. The Agency forecast the 1970s and 1980s to be decades of rapidly developing space activity. Large spacecraft for the Moon and Mars would be built and serviced in LEO. Some researchers became concerned that stray satellites might threaten planned large spacecraft and orbital facilities.

At the same time, concern increased over the possibility that objects falling from space could cause harm on Earth. After 5 years of stalemate, U.S. and Soviet negotiators made progress on the U.N.-sponsored Convention on International Liability for Damage Caused by Space Objects. The Liability Convention, as it was called, was both a vehicle for and a product of detente between the U.S. and the Soviet Union, just as was the more famous Apollo-Soyuz linkup of July 1975. Before entering into an agreement, however, U.S. negotiators wanted an estimate of the probability that their space activity would actually cause damage on Earth for which they would be held responsible. For this reason NASA launched studies of uncontrolled reentries. Some of these studies would have implications for later research into orbital debris collision hazards.

February 25 The Cosmos 397 ASAT assumes a 2203-km-by-572-km orbit at a 65.3-deg inclination and explodes near its Cosmos 394 target, producing about 120 trackable debris fragments. More than 50 remained in orbit on January 1, 1998.

Ibid.

March 31 NORAD civilian analyst John R. Gabbard publishes NORAD Analysis Memorandum 71-8, "Systematic Discontinuities in the Location of Satellite

Explosion Fragments." The document is the first to describe techniques for analyzing artificial and natural satellite breakups. It lays the groundwork for the Gabbard diagram, a widely-used graphical tool for orbital debris research (fig. 3).

Nicholas L. Johnson and Darren McKnight, *Artificial Space Debris*, revised edition, Orbit Books, 1991.

April 19 The Soviet Union launches Salyut 1, the first space station, into a 210-km-by-200-km orbit at a 51.6-deg inclination. Salyut 1 is nearly 16 m long and weighs 19,000 kg. The Soyuz 11 crew of Georgi Dobrovolski, Vladislav Volkov, and Victor Patseyev spend three weeks aboard the station (June 6-30, 1971), the longest period humans have spent in space up to this time. During reentry Soyuz 11 loses cabin pressurization and the crew perishes. No further crews are sent to Salyut 1. It is commanded to reenter in October 1971.

May 25 James McCarter, Aero-Astrodynamics Laboratory, NASA Marshall Space Flight Center (MSFC), writes a memorandum on "Space Station Satellite Collision Avoidance." He assumes a space station in a 450-500-km, 55-deg orbit. He also assumes that the NORAD catalog of space objects is a complete inventory of Earth-orbiting satellites. He determines that the space station could avoid collisions by using small rockets to change altitude by 3-4 km. This would be practical because it would expend only 9-40 kg of fuel each time. NORAD monitoring combined with a dedicated debris avoidance radar and computer on the station would provide collision warnings. McCarter calculates the collision probability to be only about 2-3 percent over 10 years.

Memorandum, S&E-AERO-MMD/Mission Design Section, NASA MSFC, May 25, 1971.

June 29-July 3 Negotiations on the Convention on International Liability for Damage Caused by Space Objects (the Liability Convention) are held in Geneva, Switzerland under auspices of the U.N. COPUOS.

David S. F. Portree, *Thirty Years Together: A Chronology of U.S.-Soviet Space Cooperation* (NASA CR 185707), February 1993, p. 14.

July 23 Morton Shaw, NASA Headquarters Safety Office, asserts in a memorandum that there must be debris in orbit too small for NORAD to detect. He states that the probability of a space station collision with orbital debris could be up to 8 percent for a 10-year period. Shaw outlines a plan to form a working group to create a NASA orbital debris program. MSFC receives primary responsibility for research. MSFC researchers continue to develop computer programs for calculating collision probabilities, but fail to include an uncatalogued debris population in their calculations.

Interview, David S. F. Portree with Donald J. Kessler, May 11, 1993; Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper).

October The U.K. becomes the sixth nation to launch a satellite on its own launch vehicle. The Prospero test satellite rides a Black Arrow rocket to LEO.

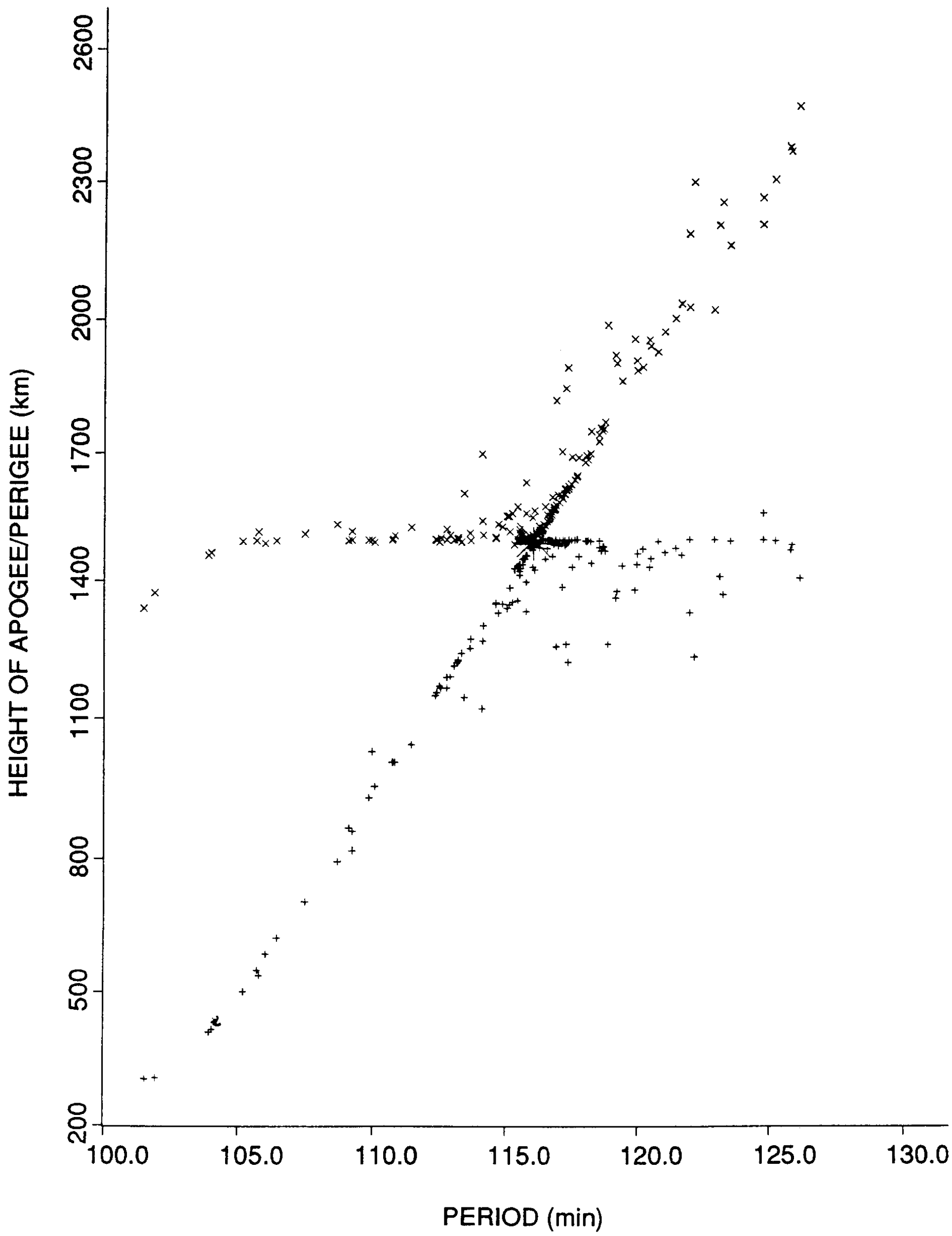

Figure 3.

The Gabbard diagram plots perigee and apogee altitudes for pieces produced in on-orbit breakups as a function of orbital period. The orbits of pieces thrown in the direction of motion of the satellite increase in apogee and period. They are plotted by the two arms on the right side of the "X"-shaped Gabbard plot. The top arm on the right side plots apogees (in this case above the satellite's original altitude), while the bottom arm shows perigees (at or near the satellite's original altitude). Pieces thrown against the orbital motion decrease in altitude and orbital period. They are plotted on the left side of the "X." Again, the top arm displays apogees (this time at or near the satellite's original orbital altitude) and the bottom arm perigees. Pieces thrown at right angles to the satellite's orbital path cluster at the center of the "X" because their orbital periods and altitudes are not changed substantially by the breakup. If no other force acted on the pieces, they would all continue to pass through the altitude at which the breakup occurred. However, atmospheric drag causes apogees to decrease over time. This effect is most noticeable on the left side of the "X," among the pieces with the lowest perigees. The left side of the Gabbard plot appears to sag over time as pieces succumb to atmospheric drag and decay from orbit.

December 1 D. E. Besette, NASA Headquarters, writes a memorandum that says collision avoidance is impractical for Skylab. He maintains that this is not necessary in any case, as the probability of a debris collision with the Orbital Workshop is only 0.01 percent.

Ibid.

December 3 Cosmos 462 enters an 1800-km-by-229-km orbit at a 65-deg inclination, then explodes near Cosmos 459. Improvements in superpower relations mean this is the last Soviet ASAT test until 1976. The test produces 29 trackable debris fragments, none of which remained in orbit by 1982.

Report on Orbital Debris, IG (Space), February 1989; Nicholas L. Johnson, "Artificial Satellite Breakups (Part 2): Soviet Anti-Satellite Programme," *Journal of the British Interplanetary Society*, Vol. 36, 1983, pp. 357-362; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, pp. 188.

1972

End of year launches reaching Earth orbit or beyond (since 1957)	1218
End of year satellites (objects in orbit)	3241

January 12 J. E. McGolrick, NASA Headquarters Space Sciences Office, circulates a memorandum summarizing the January 4 meeting of a task group on orbital debris criteria for future NASA missions. The meeting concerned uncontrolled reentry of space objects rather than collisions with orbital debris. McGolrick states that early in the meeting a NASA policy of creating no uncontrolled orbital debris was proposed; however, after discussion, the group decided that such a policy would "seriously impact science and applications spacecraft weights and costs."

Memorandum for the Record from SV/Advanced Programs and Technology Program Manager, January 12, 1972.

June 8 James McCarter publishes calculations which state that a space station with a radius of 50 m has an 8 percent probability of colliding with orbital debris if operating at 700-1000-km altitude, and a 1.5 percent probability at 440-500 km. He assumes the NORAD catalog is complete.

James McCarter, *Probability of Satellite Collision* (NASA TMX-64671), June 8, 1972.

June 15 Dr. Homer Newell, NASA Associate Administrator, and other NASA officials are briefed on orbital debris reentry hazards by members of a headquarters group assigned to study the problem. According to the transparencies used in the briefing, existing space tracking systems and early warning radars are unable to track objects throughout every orbit and are limited to northern hemisphere coverage. Available tracking systems can detect objects down to the size of a tennis ball, which includes 75-95 percent of all artificial objects in space. At the 6-cm wavelength the systems can detect objects down to the size of a walnut, but "the inventory of such objects is very limited." The officials hear that most U.S. space objects pose little uncontrolled reentry hazard, though "the Skylab hazard will be somewhat higher."

Memorandum with enclosure, PA/Senior Technical Officer William A. Fleming to FM3/Robert McAdams, July 5, 1972.

Laws for Orbital Debris: The U.N. Space Treaties of 1967 and 1972

The framers of the U.N.-sponsored space treaties of 1967 and 1972 were not aware of the hazards to space operations of orbital debris. Nevertheless, space law experts generally agree that, in the absence of international treaties dedicated to regulating orbital debris, these international agreements remain the most pertinent to the orbital debris problem.

On July 13, 1988, S. Neil Hosenball, former NASA General Counsel and U.N. Delegate, told the U.S. House Subcommittee on Space Science and Applications that Articles VI, VII, and IX of the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space (the Outer Space Treaty) can be applied to the orbital debris problem. Article VI says that state parties to the treaty bear international responsibility for their national space activities, whether sponsored by government or by private organizations. Article VII establishes the principle that a state party to the treaty which launches or procures the launch of an object into space is internationally liable for damage caused by that object to another state party of the treaty. Article IX states that state parties to the treaty should be guided by the principles of cooperation and mutual assistance. Hosenball maintained that the phrase "potentially harmful interference" can be applied to orbital debris. If a state party has cause to believe that the activities of another state party will interfere with the peaceful use and exploration of space, it may request consultation. At the same time, states planning activities which could cause interference should provide opportunity for consultation before proceeding.

According to Hosenball, the 1972 Convention on International Liability for Damage Caused by Space Objects (the Liability Convention) elaborates on Article VII of the 1967 treaty. Space objects are formally defined as including component parts of spacecraft, their launch vehicles, and component parts of their launch vehicles. Hosenball testified that this is important for the orbital debris issue because most orbital debris consists of pieces of launch vehicles.

Orbital Space Debris, Hearing Before the Subcommittee on Space Science and Applications, Committee on Science, Space, and Technology, House of Representatives, July 13, 1988.

August 13 NASA launches the Explorer 46 satellite into a 815-km-by-490-km orbit. It carries experimental Whipple Bumper meteoroid shields (fig. 4) with condenser-type impact detectors. The satellite operates between 1972-75, but data analysis is postponed until 1980-81 by funding cuts.

Interview, David S. F. Portree with Donald J. Kessler, June 1, 1993; Donald H. Humes, David R. Brooks, Jose M. Alvarez, and T. Dale Bess, "Manmade Orbital Debris Studies at NASA Langley," in *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985.

September 1 The Liability Convention, first proposed in 1966, goes into effect.

December 7-19 Apollo 17 is humankind's last flight out of LEO. Eugene Cernan and Harrison Schmitt land the LM *Challenger* at Taurus-Littrow while Ronald Evans conducts research aboard the CSM *America* in lunar orbit.

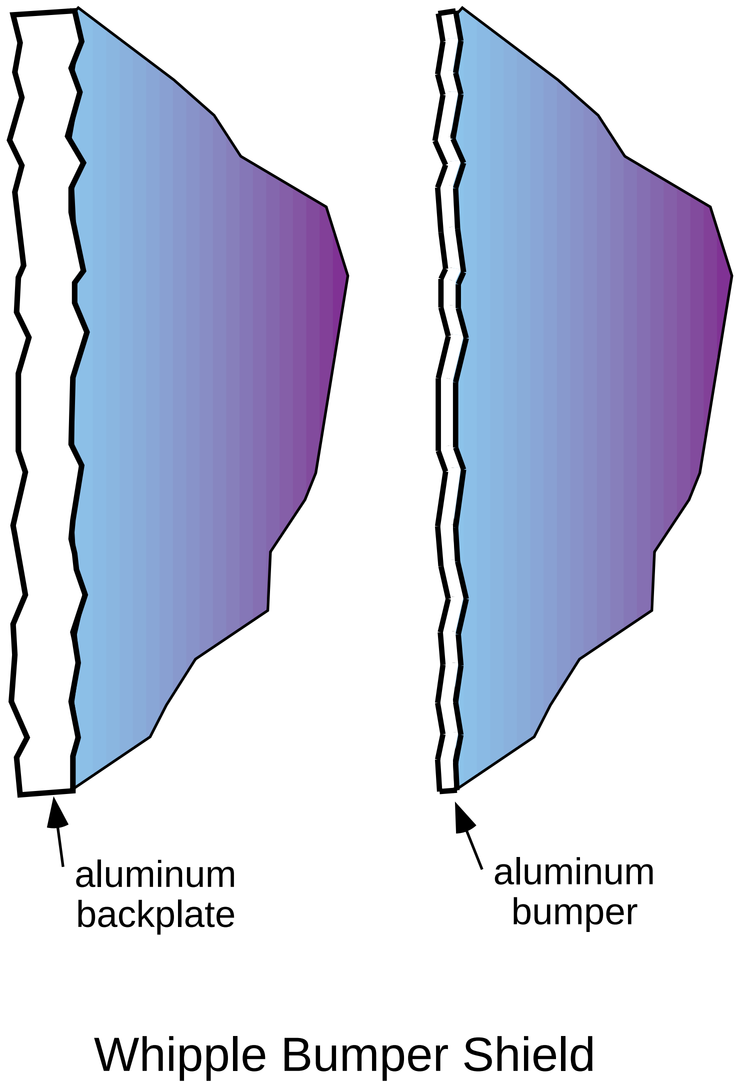

Figure 4.

The Whipple Bumper is a surprisingly effective, simple means of protecting a spacecraft from meteoroid or orbital debris impact. The energy of a particle is concentrated at its point of impact with the aluminum bumper. The bumper breaks up and partially vaporizes the particle, dispersing its energy over a broader area. This reduces the chance that damage will occur to the aluminum backplate (the spacecraft hull). The design is named for astronomer Fred Whipple, who first proposed it in 1947.

1973

End of year launches reaching Earth orbit or beyond (since 1957)	1327
End of year satellites (objects in orbit)	3527

Meteoroids

Early space scientists overestimated the threat from meteoroids. In 1946, Fred Whipple, an astronomer at the Harvard Observatory, predicted that one moonship in 25 would be destroyed by them. In 1947 he proposed a meteoroid shield design comprising an aluminum plate suspended in front of a backplate. It became known as the Whipple Bumper. In the late 1950s, meteoroid detectors on the Sputnik 3 and Explorer 3 satellites returned signals which were interpreted as indicating a meteoroid flux much higher than expected. Some space scientists invoked an Earth-orbiting dust cloud to explain this.

The Earth-orbiting dust cloud theory was countered by researchers at NASA centers and elsewhere. William Kinard, Donald Humes, and Joe Alvarez were members of a Langley Research Center (LaRC) team which studied data from the Explorer 16 and Explorer 23 meteoroid detector satellites. MSFC researchers studied data from the Pegasus satellites. Both teams found a low meteoroid flux.

Researchers at the MSC in Houston also studied meteoroids. Burton G. Cour-Palais, Subsystem Manager for Apollo spacecraft meteoroid protection, studied returned surfaces from the Mercury and Gemini spacecraft. He sponsored Herbert Zook's examination of all the Gemini windows in 1965-66. Zook found only one crater which might have been caused by a meteoroid impact. Donald J. Kessler recalculated the average meteoroid velocity, arriving at a value about half the 30 km / second previously used. By 1970, as an adjunct to his meteoroid studies, Kessler began to consider whether colliding satellites might be a source of debris pieces, just as colliding asteroids were a source of meteoroids. But cuts in meteoroid research funding stopped Kessler's work before it could begin.

The analytic (theoretical) meteoroid flux and velocity models developed by 1969 became the NASA standards for spacecraft design. The meteoroid model was used as a "ground truth" reference because it was supported by significant empirical data from both ground observation and detectors in space. (The first semi-empirical model for orbital debris was ORDEM 96, which was based on data from the ground-based radar observations and study of spacecraft surfaces that had been returned to Earth.) It became clear that spacecraft for short Earth-orbital sorties or 2-week lunar voyages required little shielding beyond their basic structures. The Skylab Orbital Workshop and Salyut space stations would be in space for month, however, so it was judged prudent to equip them with Whipple Bumper shields. Skylab's shield deployed prematurely during ascent and was torn away by atmospheric drag. Nevertheless, the three Skylab crews recorded no pressure hull penetrations before the station was abandoned in 1974. Remaining meteoroid fears quickly evaporated, and with them money within NASA for meteoroid research.

During the year LaRC conducts research into the meteoroid environment in near-Earth and interplanetary space. The study team comprises David Brooks, T. Dale Bess, Gary Gibson, Joe Alvarez, and Don Humes, and is supervised by William Kinard. The team becomes aware of the hazard posed by orbital debris after a year of work. They spend the next 2 years assessing the problem.

Ibid.

April 3 The Soviet Union launches the Salyut space station into a 248-km-by-207-km orbit. Salyut 2 is a military research station. No crews are launched to Salyut 2 because on April 14 it loses stability and tumbles, then breaks up. None of the 25 trackable pieces produced remain in orbit.

May 14

The U.S. launches the Skylab Orbital Workshop (the unmanned launch of the Orbital Workshop is officially designated Skylab 1). Skylab measures about 30 m long and 7 m wide. It carries the S149 Particle Collection experiment, which is brought back to Earth by Skylab astronauts after exposure to space. Its Principal Investigator is C. L. Hemenway of the Dudley Observatory in Albany, New York. Hemenway theorizes that the solar exosphere produces titanium particles after he finds one embedded in the experiment. Although not realized at the time, the particle was probably a paint chip.

Roland W. Newkirk, Ivan D. Ertel, and Courtney G. Brooks, *Skylab: A Chronology*, NASA Scientific and Technical Information Office, 1977, p. 386; Interview, David S. F. Portree with Donald J. Kessler, June 23, 1993.

November 16-February 8, 1974

The Skylab 4 crew of Gerald Carr, Edward Gibson, and William Pogue, the third manned Skylab launch, sets a new world spaceflight endurance record by living for 84 days aboard the Skylab Orbital Workshop. They are the last crew to live aboard Skylab.

December 29

The NOAA 3 satellite was launched on November 6, 1973 into a 1525-km-by-1522-km orbit at a 102-deg inclination. NOAA 3, also known as ITOS-F, is one in a series of more than 30 NOAA / GOES weather satellites launched since 1960. The NOAA satellites replaced the earlier TIROS series. GOES satellites operate in GEO. The NOAA satellites operate in near-polar sun-synchronous orbits. More than 120 nations receive their images. On March 28, 1983, NASA launched NOAA 8 with the first U.S. COSPAS / SARSAT international rescue system transponder. It joined two similar transponders launched on Soviet spacecraft in June 1982 and March 1983. The most recent successful NOAA satellite, NOAA 12, weighed 1416 kg when launched on May 14, 1991 (NOAA 13, launched in August 1993, failed after 12 days in orbit). NOAA 1 weighed only 306 kg when launched on December 11, 1970. About $420 million was budgeted for NOAA satellites in FY 1989-FY 1991 alone. On this date the second stage of NOAA 3's Delta launch vehicle explodes, producing nearly 200 trackable debris pieces. Of these, about 180 trackable pieces remained in orbit on January 1, 1998.

Report on Orbital Debris, IG (Space), February 1989; *Interavia Space Directory 1992-1993*, Andrew Wilson, editor, pp. 487-491.

1974

End of year launches reaching Earth orbit or beyond (since 1957)	1433
End of year satellites (objects in orbit)	3593

During the year

Burton Cour-Palais, of the Environmental Effects Office at NASA Johnson Space Center (JSC – formerly the Manned Spacecraft Center) examines the windows from the Skylab 3 and 4 Apollo CSMs. The spacecraft spent 60 and 84 days, respectively, docked to the Skylab Orbital Workshop. Cour-Palais finds numerous hypervelocity (speeds greater than 6 km / second) impact pits, presumably caused by meteoroids. He is not permitted to use Scanning Electron Microscope (SEM) analysis to identify the impactors because this would require cutting up the windows. The pits later prove to be partly the products of orbital debris strikes.

Interview, David S. F. Portree with Herbert Zook, June 16, 1993; interview, David S. F. Portree with Donald J. Kessler, June 23, 1993.

July 30

The Long Duration Exposure Facility (LDEF) project is approved. LDEF is envisioned as a reusable, bus-sized passive satellite fitted with static experiment trays. Its purpose is to let researchers learn more about the long-term effects of the space environment on a wide range of materials. LaRC is to build LDEF.

Orbital Debris Monitor, Vol. 4, No. 3, July 1, 1991; Eric Lerner, "Bringing Back a Long Look at Space," *Aerospace America*, August 1991, pp. 28-31.

September 30

Brooks, Gibson, and Bess present a paper called "Predicting the Probability that Earth-Orbiting Spacecraft will Collide with Man-Made Objects in Space," at the 25th International Astronautical Congress in Amsterdam. The paper analyzes collision probability, with special attention given to extrapolating the size of the population of small, untrackable pieces created in explosions. Brooks estimates the population of mm-size debris at only 2.5 times the catalogued population (less than the meteoroid population). A computer program error gives collision probabilities lower than those calculated by other researchers for the catalogued population. The team determines that 16.8 percent of orbiting objects are payloads; 10.1 percent are rocket bodies; 17.3 percent are payload debris; and 55.8 percent are pieces produced by explosions.

Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 1)," *Orbital Debris Monitor*, Vol. 6, No. 3, July 1, 1993; Donald H. Humes, David R. Brooks, Jose M. Alvarez, and T. Dale Bess, "Manmade Orbital Debris Studies at NASA Langley," in *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985.

1975

End of year launches reaching Earth orbit or beyond (since 1957)	1558
End of year satellites (objects in orbit)	4220

During the year

The Institute for Astronomy (INASAN) of the Soviet Academy of Science begins positional observations of GEO satellites.

Lydia Rykhlova, "Optical Observations in the Geosynchronous Orbits: Data Reduction" (not dated), Loftus Orbital Debris Files.

May 22

Landsat 1 was launched atop a Delta rocket on July 23, 1972. By March 30, 1973, when the satellite's tape recorder failed, the satellite had photographed North America 10 times and all of Earth's major landmasses at least once. The satellite returned more than 300,000 images and proved the potential of Earth observation using remote sensing. It was commanded off on January 6, 1978. To 1993 approximately $1 billion was invested in the Landsat series of satellites. Landsat 1's spent Delta second stage was left in a 910-km-by-635-km orbit at a 98.3-deg inclination after satellite separation. On this date the upper stage explodes, producing more than 225 trackable pieces. Of these, about 50 remained in orbit on January 1, 1998.

July 12

PAGEOS (Passive Geodetic Earth-Orbiting Satellite), a 30.48-m aluminized balloon, was launched on June 23, 1966. Initially it served as a target for geodesy, and was used for optical tracking experiments as late as 1972. On this date it breaks up into 11 pieces. A second breakup event was detected by Desmond King-Hele in 1976. NAVSPASUR confirmed 44 additional pieces. In addition, 19 unofficial pieces (one of which is believed to have broken into about 250 pieces) are associated with PAGEOS. The initial breakup may have been caused by a collision with a clump of dipoles produced in 1963 by the second Project West Ford experiment – they orbit at about the same altitude as PAGEOS. Later breakups could have been caused by the effects of space conditions on the materials making up the pieces. PAGEOS pieces are notoriously hard to track. According to the NASA Goddard Space Flight Center (GSFC) *Satellite Situation Report*, only a few trackable pieces of PAGEOS remained in orbit on January 1, 1998.

Interview, David S. F. Portree with Donald J. Kessler, June 23, 1993; Linda Neuman Ezell, *The NASA Historical Data Book, Volume II* (SP-4012), NASA, Washington, D.C., 1988, p. 298; *Orbital Space Debris, Hearing before the Subcommittee on Space Science and Applications, Committee on Science, Space, and Technology, House of Representatives*, July 13, 1988, p. 51; David J. Nauer, *History of On-Orbit Satellite Fragmentations*, 7th edition, July 1993, pp. 42-43; *Satellite Situation Report*, Project Operations Branch, GSFC, December 31, 1992.

July 15-26

The U.S. and the Soviet Union conduct the Apollo-Soyuz Test Project (ASTP) rendezvous and docking mission in LEO.

August 20

The NOAA 4 satellite was launched on November 15, 1974. On this date the second stage of its Delta launch vehicle explodes after 10 months in a 1461-km-by-1440-km, 101.5-deg orbit. Most of the approximately 150 trackable debris pieces produced remained in orbit on January 1, 1998.

December

Bess publishes a NASA Technical Note in which he details his contribution to the September 1974 LaRC orbital debris team paper. Bess used a light-gas gun to fire 1-gm steel and aluminum pellets at simulated spacecraft structures. This was the first attempt to calculate the mass distribution of orbital debris pieces produced in explosions and hypervelocity collisions. His data and analysis led the LaRC team to conclude that high-intensity explosions produce many small pieces. Low-intensity explosions produce fewer pieces overall. They tend to be larger than those produced in high-intensity explosions. Bess found that collisions produce a continuous distribution of large and small fragments. The results closely follow the curve of the sizes of fragments produced in asteroid collisions. Bess's work shows that these calculations apply to spacecraft structures as well. They follow a power law, which states that for every order of magnitude decrease in the diameter of the fragments, the number of fragments produced increases by 2.5 orders of magnitude.

T. Dale Bess, *Mass Distribution of Orbiting Man-Made Space Debris* (NASA TN D-8108), December 1975; Donald H. Humes, David E. Brooks, Jose M. Alvarez, and T. Dale Bess, "Manmade Orbital Debris Studies at NASA Langley," *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985.

1976	End of year launches reaching Earth orbit or beyond (since 1957)	1686
	End of year satellites (objects in orbit)	4715

Space Solar Power Energizes Orbital Debris Research at JSC

JSC Director Christopher Kraft believed that developing space solar power would be NASA's next big project after the Apollo lunar program. He wanted to build dozens of giant satellites in space to collect solar energy and beam it to Earth. This, he felt, would be a way NASA could contribute to solving the energy problem. At the same time, it would permit NASA to develop the skills needed for lunar base and Mars exploration projects of the future.

Launching the millions of tons of construction materials required for each Solar Power Satellite (SPS) and beaming energy through the atmosphere would, however, have unknown environmental consequences. The Environmental Effects Office (EEO) at JSC had been established to study the effects of frequent Space Shuttle flights on the environment. In early 1976 Andrew Potter, EEO Chief, asked Donald Kessler, an aerospace technologist in EEO, to investigate the environmental effects of building large SPSs in orbit.

Kessler reasoned that an SPS breakup caused by a collision would harm the space environment by creating a huge number of new space objects, each capable of precipitating another collisional breakup. He calculated the probabilities that collisions would occur and found that catalogued space objects were already numerous enough to pose a threat to large space platforms and stations. If the debris population continued to grow, it would soon threaten all space vehicles.

Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 1)," *Orbital Debris Monitor*, Vol. 6, No. 3, July 1, 1993; interview, David S. F. Portree with Donald J. Kessler, May 11, 1993; Donald J. Kessler, "Space Debris – Environmental Assessment Needed" (JSC 11539), July 1976.

February 9

On January 22, 1975, Landsat 2 was launched atop a Delta rocket. On this date the Delta's spent second stage undergoes the first of two explosions. The second explosion occurs on June 19, 1976. A total of more than 200 trackable pieces are created, less than 20 percent of which remained in orbit on January 1, 1998. The spent Delta second stage described a 918-km-by-745-km orbit at a 97.8-deg inclination before the first explosion.

July

Donald Kessler warns that fragmentation by impact between debris pieces will exponentially increase the debris population. Runaway debris generation could begin as early as the year 2000. The starting condition for his estimate is the orbital population in the NORAD catalog. Based on data from meteoroid impact experiments conducted in the late 1960s by McDonnell Aircraft Company to support Mars expedition planning, he assumes that each collision will produce 100 pieces. Kessler concludes that the probability of debris collision for a space station with a radius of 50 m over 10 years could be 100 percent by the year 2010.

Donald J. Kessler, "Space Debris – Environmental Assessment Needed" (JSC 11539), July 1976; Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper).

July 31-August 1

Preston Landry, a civilian analyst at NORAD, conducts the Unknown Satellite Track Experiment at the request of the LaRC orbital debris team. It lasts about 12 hours. The experiment uses the Perimeter Acquisition Radar Characterization System (PARCS) radar in North Dakota. PARCS is a phased array of 6144 north-facing sensors which can track many objects simultaneously in a 65-deg wide sector to 4000 km north of the radar site. During the experiment, the radar detects 8445 objects, 17.7 percent of which are not listed in the NORAD catalogue. Of the objects detected below 400 km, 90 percent are previously undetected. The explanation reached for the larger number of small, previously unknown objects in lower orbits is that unknown objects too small to be detected at higher altitudes rain down to lower altitudes, where they can be detected. This is one of the most important findings of the 1976 PARCS test. However, the breakup of the Soviet Cosmos 844 satellite only a few days before the test may have inflated the number of objects at low altitudes beyond its usual level.

Donald J. Kessler, "NORAD's PARCS Small Satellite Tests (1976 and 1978)," *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985, p. 39-44.

October 26 The Soviet Union launches the Ekran 1 television relay satellite into GEO at 99 deg east. It is the first Direct Broadcast Satellite (DBS). Ekran satellites weigh 1970 kg and keep station to within about 0.5 deg of their GEO slot.

November David Brooks publishes NASA TMX-73978, *A Comparison of Spacecraft Penetration Hazards Due to Meteoroids and Manmade Earth-Orbiting Objects*. He applies the findings of the September 1974 Brooks, Bess, and Gibson paper to calculate the probability of penetrations by orbital debris and natural meteoroids for double-walled spacecraft, such as the Skylab Orbital Workshop. He shows that the Whipple Bumper is adequate for meteoroid protection, but not for orbital debris protection. Brooks also determines that while orbital debris pieces are generally larger and slower than meteoroids, spacecraft in high-inclination orbits risk collisions with orbital debris at speeds up to 15 km/second. He asserts that debris cleanup and avoidance are too expensive, so spacecraft walls must be strengthened to contend with the hazard.

Donald H. Humes, David E. Brooks, Jose M. Alvarez, and T. Dale Bess, "Manmade Orbital Debris Studies at NASA Langley," *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985; Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper).

December 24 The Delta upper stage which placed the NOAA 5 satellite into orbit on July 29, 1976 explodes, producing 159 trackable debris pieces. Of these, 153 remain in orbit on January 1, 1998.

December 27 The Cosmos 886 ASAT explodes, producing 72 trackable pieces of debris. Of these, 55 remain in orbit on December 31, 1992.

Nicholas L. Johnson, "Artificial Satellite Breakups (Part 2): Soviet Anti-Satellite Programme," *Journal of the British Interplanetary Society*, Vol. 36, 1983, pp. 257-262.; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 188.

1977	End of year launches reaching Earth orbit or beyond (since 1957)	1810
	End of year satellites (objects in orbit)	5202

February 17

At the request of Joseph P. Loftus, Jr., Chief, Technical Planning Office at JSC, Donald Kessler submits a memorandum proposing that optical sensors (telescopes) be used to detect LEO orbital debris. Kessler's proposal is modified to become the second PARCS radar test.

Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 1)," *Orbital Debris Monitor*, Vol. 6, No. 3, July 1, 1993.

June

Donald Kessler and Burton Cour-Palais predict that the hazard posed by orbital debris will soon exceed the hazard from meteoroids. They state that the collision rate between objects in 150-4000-km orbits was 0.013 per year in 1976. They note that the number of objects NORAD tracks has increased by 320-510 objects per year since 1966, and predict that the collision rate will increase rapidly.

Burton Cour-Palais and Donald J. Kessler, "Space Debris – Environmental Update I" (JSC 12949), June 1977; Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper).

June 30

In a formal briefing on SPS environmental impact, Donald Kessler describes to Christopher Kraft the hazard posed by orbital debris. According to Joseph Loftus, "in general [Kraft] had a 'show-me' kind of attitude" because of his mission operations background. Kraft is skeptical of Kessler's orbital debris conclusions because they are largely theoretical.

Interview, David S. F. Portree with Donald J. Kessler, June 7, 1993; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

July

The JSC SPS Systems Definition effort publishes a report titled *Solar Power Satellite: Concept Evaluation*. Section VII, entitled "Environmental Factors," reports that predictions of collision frequency contain a large measure of uncertainty. This is because the number of orbiting objects below the level of NORAD radar detectability down to about 1 mm and the number of "ejected 'daughter' products" are not known. It gives the uncertainty in collision frequency for the year 2000 as about four orders of magnitude. According to the report, "this uncertainty implies the need to be very careful to minimize the rate at which new objects are added to orbit (especially small, numerous objects) and a possible need for removing debris ('space cleanup') at some later date." To reduce uncertainty, the report calls for improvement of space debris models and the small object database. It also calls for structural designs which minimize the effects of damage, identification of crew safety design requirements, and consideration of "trade-offs among constraints on the generation of additional space debris and requirements for debris removal."

Solar Power Satellite: Concept Evaluation, Vol. 1, July 1977, pp. VII-4; interview, David S. F. Portree with Donald J. Kessler, June 1, 1993.

1977

July 14

A Delta rocket lifts off from Cape Canaveral, launching the first Japanese GMS (Himawari 1) weather satellite toward a slot in GEO at 140 deg east longitude. Soon after payload separation the second stage explodes in a 2025-km-by-53-km orbit at a 29-deg inclination. The low-inclination orbit is unusual for an exploding Delta second stage – previous Delta explosions took place in high-inclination, sun-synchronous orbits. The explosion produces nearly 170 trackable pieces, of which 45 percent remained in orbit on January 1, 1998.

Interavia Space Directory 1992-93, Andrew Wilson, editor, p. 480; *Report on Orbital Debris*, IG (Space), February 1989.

September 25-October 1

Lubos Perek, a Czech astronomer and Chief, Outer Space Affairs Division, General Secretariat of the U.N., presents "Physics, Uses and Regulation of the Geostationary Orbit, or, ex facto sequitur lex," at the 28th International Astronautical Federation congress in Prague, Czechoslovakia. Perek describes aspects of the GEO environment arising from solar radiation pressure, the ellipticity of the equator, and Earth's oblateness, then lays out how they create problems for satellites in GEO. The paper is among the first to address GEO orbital debris.

Lubos Perek, "Physics, Uses, and Regulation of the Geostationary Orbit, or, ex facto sequitur lex" (IAF Paper SL-77-44), presented at the 28th International Astronautical Federation Congress, Prague, Czechoslovakia, September 25-October 1, 1977.

September 29

The Soviet Union launches Salyut 6, the fifth Soviet space station to host a crew, into a 51.6-deg, 256-km-by-214-km orbit. Salyut 6 is generally similar to Salyut 1. However, it has a rear docking port. Automated Progress supply ships call at the rear port, delivering supplies for the crew and fuel to maintain the station's orbit. Salyut 6 can thus remain operational much longer than the earlier Salyuts. Cosmonauts live aboard Salyut 6 for a total of 676 days up to 1982. Salyut 6 is visited in April 1981 by the Cosmos 1267 expansion module, which nearly doubles its 13.5-m length. It receives the first international spaceship crew (Alexei Gubarev and Vladimir Remek, a Czech, the first non-Soviet / non-American in space). The Soyuz 35 crew of Leonid Popov and Valeri Ryumin spends a record 185 days on the station.

December 21

ASAT weapon Cosmos 970 explodes in a 1139-km-by-946-km orbit at a 65.8-deg inclination. Of the 70 trackable pieces produced, all but four remained in orbit on January 1, 1998.

Nicholas L. Johnson, "Artificial Satellite Breakups, (Part 2): Soviet Anti-Satellite Program," *Journal of the British Interplanetary Society*, Vol. 36, 1983, pp. 356-363; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 188.

1978	End of year launches reaching Earth orbit or beyond (since 1957)	1934
	End of year satellites (objects in orbit)	5170*

*The decline since 1977 was caused by record-high levels of solar activity during the 1978-1980 solar maximum period.

During the year John Gabbard tells Donald Kessler how to identify breakup fragments in the NORAD catalog. Using a limited list, Kessler draws a "4 percent random sample" of about 100 objects, then tracks the origin of each object. He notices that a large fraction originate with Delta second stages launched since 1972. (Many were left in sun-synchronous orbits.) Kessler informs Loftus, who in turn informs the Expendable Launch Vehicle (ELV) Office at NASA Headquarters. A series of informal discussions commence between the ELV Office, JSC, and the Delta Program Office at GSFC. The ELV Office contracts with Battelle Institute, Columbus, Ohio, to study the orbital debris issue. Donald Edgecombe, who has experience with the related issue of uncontrolled reentry of space objects, organizes the Battelle effort.

Interview, David S. F. Portree with Donald J. Kessler, May 11, 1993.

January 24 Cosmos 954, a Soviet nuclear-powered RORSAT ocean surveillance satellite, undergoes uncontrolled reentry over northern Canada.

Heightened Awareness: The Skylab and Cosmos 954 Reentries

The Soviet Union launched Cosmos 954 on September 18, 1977. The satellite carried a nuclear reactor to provide adequate electricity for its powerful ground-pointing radar. Cosmos 954, like other RORSATs, operated in a low orbit, with a limited lifetime before decay. It had to be periodically reboosted to maintain orbit. Normally, when its reboost fuel supply was nearly depleted, such a satellite launched its reactor into a high storage orbit with a lifetime of 300-1000 years (the nuclear fuel in the reactor has a half-life of 70,000 years, however, meaning that the storage orbit foists contending with the radioactives on a future generation). The main body then reentered harmlessly. Cosmos 954 malfunctioned, however, and reentered with its reactor still attached on January 24, 1978. The Soviets announced that the reactor contained about 30 kg of enriched uranium. Cosmos 954 broke apart over the Great Slave Lake, in northwestern Canada, and peppered a region 800 km long with radioactive debris. Cleanup cost $14 million. The 1972 Liability Convention came into play. Canada claimed $6 million and the Soviets eventually paid $3 million. The Soviets redesigned the reactor boost system and resumed launching RORSATs in April 1980.

The uncontrolled reentry increased awareness at the U.S. Cabinet level of potentially dangerous space objects. The U.S. Secretary of State, Zbigniew Brzezinski, raised the issue in a public speech. He declared that "no one [in any U.S. government agency] shall increase the hazard in space without consulting me."

By this time the 80,000-kg Skylab Orbital Workshop had been in orbit for almost 6 years. As early as 1976, the National Oceanic and Atmospheric Administration (NOAA) predicted that Skylab would decay from orbit earlier than the March 1983 date forecast by NASA. By 1977, the 11-year sunspot cycle was already climbing toward the most intense solar maximum period before 1989-91. As is normal during active Sun periods, increased solar heating expanded Earth's upper atmosphere. But the 1978-80 solar maximum expanded the upper atmosphere to an unusual degree, hastening Skylab's decay.

1978

Less than a month after the Cosmos 954 reentry, NASA announced that Skylab would decay below 278 km by October 1979. As Skylab fell, worldwide concern grew. The space agency took pains to regain partial control over Skylab. However, the chances that pieces of Skylab would hit a person or cause property damage were extremely small. On July 11, 1979, Skylab reentered over the Atlantic Ocean. The crew of an aircraft flying at 8500 m over the Indian Ocean saw Skylab appear as a blue fireball in the starry predawn sky. After 45 seconds, the fireball turned red-orange and broke into five large pieces. Early-risers throughout southwestern Australia saw flaming pieces in the sky. Sonic booms awoke sleepers in Perth and Kalgoorlie, the largest cities in Skylab's path. Skylab rained debris in a footprint more than 1000 km long and nearly 200 km wide. Some 500 major debris pieces, with a total weight of about 20,000 kg, were found in the Outback.

Together, the Cosmos 954 and Skylab reentries increased awareness that orbiting objects could pose hazards, that the products of human space activities did not vanish into infinite blackness when their usefulness ended. The reentries helped create a climate in which orbital debris research and awareness-building efforts could continue to develop.

W. David Compton and Charles D. Benson, *Living and Working in Space: A History of Skylab*, NASA Scientific and Technical Information Branch, Washington, D. C., 1983; Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 1)," *Orbital Debris Monitor*, Vol. 6, No. 3, July 1, 1993; interview, David S. F. Portree with Donald J. Kessler, May 11, 1993; Craig Covault, "Skylab Tumble Timing Linked to Control," *Aviation Week & Space Technology*, July 16, 1979, pp. 22-23; "Cosmos Reentry Spurs Nuclear Waste Debate," *Aviation Week & Space Technology*, January 30, 1978, p. 33.

February 7 The U.S. Senate Subcommittee on Science, Technology, and Space takes testimony from Dr. William M. Brown of the Hudson Institute, NASA Administrator Dr. Robert A. Frosch, and others on the future in space. Brown describes as "chilling" some of the conclusions on orbital debris reached by Donald Kessler and Burton Cour-Palais in their paper for the *Journal of Geophysical Research*. He requested an advance copy in late 1977. In a letter to Kessler acknowledging use of the paper in his testimony, Brown reflects the contemporary international political climate by stating that "Russian killer satellites [Cosmos ASATs] are killing the future of space." At this time few people suspected that the major source of orbital debris was exploding U.S. Delta second stages.

Interview, David S. F. Portree with Donald J. Kessler, June 1, 1993; letter, William M. Brown, Hudson Institute, to Donald J. Kessler, April 3, 1978.

March 14 The Delta second stage which placed Geodynamics Experimental Ocean Satellite (GEOS) 3 in orbit on April 9, 1975 breaks up in an 847-km-by-807-km orbit at an inclination of 115 deg, producing only four trackable pieces. Three remained in orbit on January 1, 1998.

June 1 Donald Kessler and Burton Cour-Palais publish "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt" in the *Journal of Geophysical Research* (JGR). The article is based on their June 1977 JSC document. It proves to be a seminal work on the orbital debris problem. They predict that collisional breakup will become a new source of orbital debris, "possibly before the year 2000," and that the debris flux will continue to increase over time once collisional breakup begins, even if no new payloads are placed in Earth orbit.

Donald J. Kessler and Burton G. Cour-Palais, "Collision Frequency of Artificial

Satellites: The Creation of a Debris Belt," *Journal of Geophysical Research*, Vol. 83, No. A6, pp. 2637-2646.

June 23 The Soviet Ekran 2 DBS undergoes a nickel-hydrogen battery explosion in GEO. The Soviets photograph the breakup. No other space power detects the explosion.

"Russia Seeks Joint Space Test to Build Joint Military Cooperation," *Aviation Week & Space Technology*, March 9, 1992, pp. 18-19; interview, David S. F. Portree with Donald J. Kessler, August 3, 1993.

August 21-23 In six 84-minute sessions, the PARCS detects 5586 known objects, 437 unknown objects, and 379 uncorrelated (not tracked well enough to determine their status) objects. Including the uncorrelateds is the only major departure from the 1976 PARCS experiment. The percentage of unknowns nearly doubles directly over the radar site, where sensitivity is highest. 80 percent of the objects detected below 300 km are unknown. Only 32 percent above 2000 km are unknown. Many unknowns are found at inclinations of 62 deg-64 deg, 84 deg-88 deg, and 103 deg-106 deg. The second group may be associated with the second Project West Ford experiment in 1963. No recent debris-producing events compromise the results, as may have happened in 1976. This adds credibility to the idea that previously unknown small debris found in low orbits originates at higher altitudes.

Donald J. Kessler, "NORAD's PARCS Small Satellite Tests (1976 and 1978)," *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985, pp. 39-44.

December 19 Donald Kessler again briefs Kraft on orbital debris. The PARCS experiments provided concrete data on the uncatalogued orbital debris population, so Kraft is willing to accept that a problem exists. He sanctions further research.

Interview, David S. F. Portree with Donald J. Kessler, June 1, 1993.

1979

End of year launches reaching Earth orbit or beyond (since 1957)	2040
End of year satellites (objects in orbit)	5035*

*The decline since 1978 was caused by record-high levels of solar activity during the 1978-1980 solar maximum period.

February 6-8 Christopher Kraft presents a paper at the 15th American Institute of Astronautics and Aeronautics (AIAA) Annual Meeting and Technical Display in Washington, D.C. Titled "The Solar Power Satellite Concept – The Past Decade and the Next Decade," it touches on the hazards of meteoroids and orbital debris. He asserts that experience gained from past space activities shows that protection can be provided at reasonable cost. Kraft adds that a "'space cleanup' of past man-made orbital debris may become desirable during the SPS construction phase, and meticulous housekeeping during construction will become imperative."

Christopher C. Kraft, Jr., "The Solar Power Satellite Concept – The Past Decade and the Next Decade," AIAA 79-0534, February 1979.

1979

March 9 Burton Cour-Palais telephones Donald Kessler to tell him "our work has hit pay dirt" at NASA Headquarters. Cour-Palais tells Kessler that Philip Culbertson, Deputy Associate Administrator (Technology) in the NASA Headquarters Office of Space Transportation Systems, raised the orbital debris issue during negotiations with the Soviets on the second Strategic Arms Limitation Treaty (SALT 2).

Kessler Phone Logs, 1978-1982

March 26 Joseph Loftus again arranges for Donald Kessler to brief Christopher Kraft and his senior managers. When asked if orbital debris research should continue at JSC, Kraft says, "we would be crazy not to continue. . . go do it. . . forthwith." According to Kessler, this was "the directive that allowed the orbital debris program to be developed."

Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 1)," *Orbital Debris Monitor*, Vol. 6, No. 3, July 1, 1993.

July 11 The U.S. Skylab Orbital Workshop reenters, raining debris on Australia.

September 16-22 Lubos Perek presents "Outer Space Activities *versus* Outer Space" at the 22nd Colloquium on the Law of Outer Space in Munich, West Germany. Perek's paper presents an overview of the orbital debris issue as understood at this time. Perek depicts an optimistic future in which the U.S. Space Shuttle, Soviet Progress automated space station supply ships, and the European Ariane rocket provide easy access to space. He maintains that easy access to space will cater to large space structures, such as solar power satellites and space habitats. Perek states, however, that "there is. . . one aspect which is rarely mentioned in this connection. . . how will the individual projects and missions relate to each other?" He notes that at present the only acknowledged relationship between satellites is their common use of the radio frequency spectrum for communications. Perek asserts that collision is another way space objects will relate to each other, though because space is perceived to be large relative to the number of intact satellites in Earth orbit (about 1000 at this time), the risk of collision is usually discounted. Perek points out that relative velocity and cross sectional area are also factors that affect collision probability. Perek asserts that "satellite cross section will assume its importance at a more distant future. Since the collision probability is proportional to the area of the satellite, the picture will be entirely different for solar power stations with an area of several square kilometers than it is for present day satellites." Perek also points out that the 1000 satellites in orbit are attended by about "3500 debris large enough to be tracked by radar and an unknown number of small debris, nuts and bolts, and fragments weighing a fraction of a gram, which escape tracking and detection." He asserts that "the small debris are not without danger." Perek cites Donald Kessler and Burton Cour-Palais's 1978 paper in the *Journal of Geophysical Research* and David Brooks' November 1976 NASA report when describing the small debris environment and future runaway debris generation. Perek then states that "preventing all collisions is impossible. Minimizing their effects is and will be expensive, but it is a bargain price compared to the repair of damage." Specifically, he calls for

- reducing the amount of debris produced during launch and operations
- deorbiting inactive satellites
- placing inactive satellites into disposal orbits
- "using non-intersecting orbits in specific areas of outer space."

Perek goes on to suggest that "the spirit of the Rule of Good Seamanship" could be a basis for future space traffic regulation. Finally, Perek states that "the operators of space objects discharge larger responsibilities than the many operators of vehicles on roads, in the seas, and in the air," so it is appropriate for "the international community to adopt regulatory or recommendatory measures wherever and to whatever degree is found necessary."

Lubos Perek, "Outer Space Activities *versus* Outer Space," in *Proceedings of the 22nd Colloquium on the Law of Outer Space*, Munich, West Germany, AIAA, 1980, pp. 283-286; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

September 24

Christopher Kraft writes to John F. Yardley, NASA Associate Administrator for Space Transportation Systems, to explain his request that orbital debris be discussed at a NASA Management Council meeting. Kraft originally asked to brief the Council at its September meeting, but Yardley struck the briefing from the agenda. According to Joseph Loftus, Yardley did this because "orbital debris was an unpleasant subject and he didn't want to talk about it." In addition, Yardley was fully occupied with moving the Space Shuttle toward flight. Kraft tells him that his motive in putting the matter on the agenda "was to introduce you to the implications of the growing population of man-made objects in space. This situation is one we will have to face some time in the future." Kraft summarizes JSC's findings by stating that "the man-made population is very real and detectable," and that while "this population is the subject of continuous measurement. . . there may be a significant gap in measurements of smaller objects." He admits that, "the present population does not. . . warrant any immediate changes to our current mission planning; however, it is increasing and could become self-propagating." Kraft concludes by saying that "corrective measures are evident and should be considered." These include "policy control measures and operational practices to curtail unnecessary population growth; the establishment of an environmentally acceptable population flux model; and the management of programs to operate within the limits of the flux model." In connection with this last point, he states that "we have brought the unusually large debris contribution of the Delta second stage to the attention of the Expendable Launch Vehicles Program Office." Joseph Loftus drafted the letter for Kraft.

Letter, Christopher Kraft, JSC, to John F. Yardley, NASA Headquarters, September 24, 1979; note, Joseph P. Loftus, Jr. to David S. F. Portree, August 2, 1993; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

October

The NASA Headquarters Advanced Programs Office, a part of the Office of Space Transportation Operations, provides the JSC orbital debris team with

$70,000 to fund its activities. This is the first funding at JSC specifically for research into the orbital debris problem.

Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 2)," *Orbital Debris Monitor*, Vol. 6, No. 4, October 1, 1993.

October 22-23 JSC researchers and engineers discuss space nuclear power systems with U.S. Department of Energy (DOE) contractors. The contractors tell NASA that nine U.S. nuclear power sources orbit Earth, with others planned. One is a reactor. The others are radioisotope thermal generators (RTGs). Six of the seven LEO satellites are in high-inclination orbits, increasing the risk that they will collide with other objects and break up. Only three of the satellites can be recovered by the Space Shuttle, and then only by using Orbital Maneuvering System (OMS) kits to augment the Shuttle's baseline rendezvous capability. The nuclear reactor cannot be reached even using three OMS kits in series. The meeting produces a summary which states that the previous estimate of the lifetime of nuclear devices in orbit – 150 years or longer – "is now questionable safety criteria because of collision." The radioactive pieces from fragmented nuclear devices can be expected to decay from orbit before radioactive decay can render them harmless. The summary notes that JSC is developing a program to define the severity of the orbital debris problem in general and develop control techniques. It reports that no GEO satellite recovery capability is planned for the Shuttle, and that Shuttle enhancements (such as OMS kits) are just beginning to be studied. However, "NASA is in the preliminary phase of defining a system concept [a space tug] that could provide a variety of services including deployment, inspection, retrieval, support, and Earth return." The DOE requests that NASA include the nuclear-powered satellites in its collision studies. It also asks the space agency to determine Shuttle requirements for rendezvous with and servicing of nuclear-powered satellites in LEO and GEO. The DOE states that it will determine a disposal method for nuclear-powered satellites. Possibilities listed are controlled reentry, return by Shuttle to Earth, and insertion by unspecified means into solar orbit at 0.82 astronomical units (inside Earth's orbit).

Memorandum with Attachment, EW4/Reuben Taylor to EW4/Chief, Systems Design Office, October 25, 1979.

Late November The Snapshot satellite carries SNAP 10-A, the only U.S. space nuclear reactor launched to date. On this date Snapshot undergoes what orbital debris researchers term "an anomalous event." The parent body sheds pieces but remains largely intact. Six more anomalous events occur in the next 6 years, releasing nearly 50 trackable pieces. Release of radioactives is possible but not confirmed. A collision with another space object has not been ruled out as the cause of the initial event, though an unknown internal malfunction is perhaps more likely. SNAP 10-A shut down prematurely in May 1965, 43 days after launch. The main body of the satellite remains in a 1316-km-by-1268-km orbit at a 90.3-deg inclination. Expected orbital lifetime is more than 3000 years (assuming it avoids a more complete breakup).

Nicholas L. Johnson and Darren McKnight, *Artificial Space Debris*, revised edition, Orbit Books, 1991; David J. Nauer, *History of On-Orbit Satellite Fragmentations*, 7th edition, Teledyne Brown Engineering, July 1993, p. 266; Joseph A. Sholtis, Jr., *et al*, "U.S. Space Nuclear Safety: Past, Present, and

Future," presented at the Tenth Symposium on Space Nuclear Power and Propulsion, Albuquerque, New Mexico, January 10-14, 1993.

December 24

The European Space Agency (ESA) launches its first satellite, the CAT test vehicle, atop an Ariane 1 rocket. The flight is designated V1. The third stage is left in a 21,510-km-by-178-km orbit at a 17.8-deg inclination. The Ariane V1 third stage apparently exploded in orbit on March 1, 1980. However, the Goddard *Satellite Situation Report* for December 31, 1992, lists only two catalogued objects associated with V1, both of which decayed by 1990. Low perigee means most of the debris produced decays rapidly. Detection and tracking of debris from this event was difficult because of the low inclination and high apogee of the orbit.

Space Log 1957-1991, TRW, 1992, p. 182; David J. Nauer, *History of On-Orbit Satellite Fragmentations*, 7th edition, Teledyne Brown Engineering, July 1993, p. 138; *Satellite Situation Report*, Project Operations Branch, GSFC, Vol. 32, No. 4, December 31, 1992, p. 253.

1980

End of year launches reaching Earth orbit or beyond (since 1957)	2145
End of year satellites (objects in orbit)	5011*

*The decline since 1979 was caused by record-high levels of solar activity during the 1978-1980 solar maximum period.

Beginning this year

During the first half of the 1980s, Donald Kessler, Joseph Loftus, and Burton Cour-Palais present tutorial briefings on orbital debris to the Department of State, U.S. Air Force Space Division, Department of Transportation (DOT), NORAD, NASA centers, and other government organizations and agencies. Most of the briefings were organized by Loftus.

Interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

During the year

This year Herbert Zook, Uel Clanton, and Richard Schultz, all of the Geology Branch, Planetary and Earth Sciences Division, JSC, analyze impact pits in the Skylab 4 Apollo CSM windows. Zook and Schultz count and measure the pits. Clanton then uses SEM analysis to determine that half of the pits (predominantly the smallest) are lined with aluminum expelled from solid rocket motors. They conclude that, in their size range (smaller than 30 microns), aluminum particles already outnumber meteoroids in near-Earth space.

Interview, David S. F. Portree with Herbert Zook, June 16, 1993; Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 2)," *Orbital Debris Monitor*, Vol. 6, No. 4, October 1, 1993.

January 14

David H. Suddeth, Space Technology Division, GSFC, contacts Donald Kessler at JSC for information on orbital debris to aid him in preparing a proposal for a GEO satellite reboosting program. Suddeth calls the proposed program "Death with Dignity." It calls for GEO satellites to be boosted to graveyard orbits above GEO at the end of their useful lives. Suddeth later briefs NASA Headquarters Chief Engineer Walter C. Williams on the proposal. At the JSC orbital debris workshop in July 1982 he describes GEO satellite problems. Suddeth states that "NASA is considering establishing a policy for the limitation of the physical crowding of the geostationary orbit. This paper was requested by the Director, Communication and Data Systems Division, Code TS, NASA HQ." In "Recommendations for Action," Suddeth calls for NASA policy to state that

- The GEO insertion burn should be accomplished using a motor which remains attached to the spacecraft after the burn.
- No objects should be released from spacecraft in GEO.
- Fuel should be retained to boost GEO spacecraft to non-synchronous graveyard orbits.
- Spacecraft should be disposed of into higher (westward drifting) graveyard orbits, if possible, "to avoid communication interruption and impeding later arrivals."
- Governmental policy should require that all GEO users "desynchronize" GEO satellites before they exhaust their fuel.
- "NASA and the U.S. should strive to establish a world-wide policy for removal, binding on all users of the geosynchronous orbit."
- "Ultimately, NASA should plan and carry out a procedure for clearing dead spacecraft and debris from the geosynchronous orbit."

David H. Suddeth, "Debris in the Geostationary Ring – the Endless Shooting Gallery – the Necessity for a Disposal Policy," *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985; interview, David S. F. Portree with Joseph P. Loftus, Jr., September 9, 1993.

March 31

The Ad Hoc Working Group on Space Debris and Geostationary Crowding meets at NASA Headquarters. Its members include representatives from NASA Headquarters, GSFC, and JSC. The meeting aims "to establish communication among those concerned with some aspect of debris and its consequences; to define, in broad terms, a base of common information as to the scope and significance of the debris problem; and to determine what steps, if any, could or should be taken to provide within NASA a coherent framework for pursuing further coordinated activity with respect to space debris and geostationary crowding."

Marta Cehelsky, "Issues Paper: Space Debris," Meeting Summary Prepared for Deputy Administrator Alan Lovelace "at the request of Mr. Culbertson," June 2, 1980.

April 18

The Soviets launch Cosmos 1174 in pursuit of the Cosmos 1171 target satellite. The ASAT satellite explodes 60 km from the target, so the test is considered a failure. Of the more than 40 trackable debris pieces produced, less than 10 remained in orbit on January 1, 1998. About 6 percent of the debris tracked in 1983 originated in Soviet ASAT explosions.

Gautam Badhwar and Phillip Anz-Meador, "Mass Estimates in the Breakups of Soviet Satellites," *Journal of the British Interplanetary Society*, Vol. 43, No. 9, September 1990, pp. 403-410; Nicholas L. Johnson, "Artificial Satellite Breakups (Part 2): Soviet Anti-Satellite Programme," *Journal of the British Interplanetary Society*, Vol. 36, 1983, pp. 356-363; *Satellite Situation Report*, Project Operations Branch, GSFC, December 31, 1992.

April 29 The Soviet Union launches Cosmos 1176, the first RORSAT nuclear-powered ocean surveillance satellite launched since Cosmos 954 scattered radioactive debris across northwestern Canada in January 1978. The U.S. State Department issues a "Statement of Regret" chiding the Soviets for resuming RORSAT operations.

Interavia Space Directory 1992-93, Andrew Wilson, editor, p. 192.

June The AIAA Technical Committee on Space Systems begins a formal review of the orbital debris problem in preparation for writing an AIAA position paper on the subject.

July 18 India launches its first satellite, Rohini 1B, atop an SLV-3 launch vehicle. The 40-kg test satellite describes a 745-km-by-295-km orbit at a 44.7-deg inclination. It decays from orbit on May 20, 1981.

November 23 Three fuses blow on the Solar Maximum Mission (Solar Max) satellite, which was launched in February 1980. Four of its six telescopes lose pointing ability. Solar Max has a modular design to permit routine servicing by Space Shuttle astronauts, so NASA schedules a Shuttle mission to repair the satellite. The usefulness of its Gamma Ray Spectrometer is reduced by anomalous gamma ray emissions. In 1988 these are revealed to have been traced to Soviet RORSAT nuclear reactors.

Nicholas L. Johnson, *The Soviet Year in Space 1989*, pp. 83-84.

1981

End of year launches reaching Earth orbit or beyond (since 1957)	2268
End of year satellites (objects in orbit)	5451

During the year Cutbacks in NASA meteoroid research funding in the mid-1970s forced Donald Humes at LaRC to postpone analysis of Explorer 46 meteoroid data until 1980-81. Donald Kessler reviews Humes' paper on the Explorer 46 data. Using raw data included in the paper, Kessler detects directionality in the impacts on Explorer 46. He believes this indicates a population of small Earth-orbiting debris objects. The impacts show a correlation with solid rocket motor firings in orbit. This is difficult to explain, as the aluminum oxide particles produced by solid rocket motors are believed to be too small to trigger the Explorer 46 detectors.

Interview, David S. F. Portree with Donald J. Kessler, June 1, 1993.

January 27 The Delta second stage which placed the Landsat 3 and Oscar 8 satellites in near-polar, 98.9-deg inclination orbits on March 5, 1978, explodes into more than 200 trackable pieces while over Antarctica. About 140 trackable pieces remained in orbit on January 1, 1998. The JSC orbital debris team writes a memorandum on the breakup to NASA Headquarters, which is subsequently passed on to McDonnell Douglas Space Systems Company, the maker of the Delta rocket.

Ibid; Nicholas L. Johnson, “Preliminary Analysis of The Fragmentation of the Spot 1 Ariane Third Stage,” *Orbital Debris from Upper-Stage Breakup*, Joseph P. Loftus, Jr., editor, 1989, pp. 41-106.

March Joseph Mahon, Director of the ELV Office in the Office of Space Transportation Operations at NASA Headquarters, issues a directive to the Delta Program Office at GSFC calling for an investigation into Delta breakups.

Ibid.

April 5 On this date, pieces from Delta second stage explosions make up about 27 percent of the 3904 tracked objects with orbital periods under 225 minutes.

Nicholas L. Johnson, “The Crowded Sky: The Danger of Collisions in Geostationary Orbit,” *Journal of the British Interplanetary Society*, Vol. 24, No. 12, December 1982, pp. 446-449.

April 12 NASA launches Columbia on the first Space Shuttle mission, STS-1. When the Shuttle was designed in the 1970s, orbital debris was not a recognized hazard. In the latter half of the 1980s cost per flight was estimated at $200-400 million. Orbiter replacement cost was estimated at $1-2 billion. Each orbiter is 37 m long and 24 m wide across its delta wings. Crew complement is variable, depending on mission requirements; STS-1 carried 2 crew, and flights prior to the Challenger accident carried as many as 8 crew. In its April 1990 report, the U.S. Government Accounting Office (GAO) stated that an unnamed NASA orbital debris expert had estimated that most of the orbiter surfaces will not be penetrated by debris particles 0.4 cm or smaller, while the triple-paned windows require a hit from at least a 1.5-cm object before loss of cabin pressure will occur.

Space Program Space Debris: A Potential Threat to Space Station and Shuttle, GAO, April 1990.

May The NORAD / ADCOM Directorate of Analysis publishes TM 81-5, “The Explosion of Satellite 10704 and Other Delta Second Stage Breakups.”

May 6 Nimbus 7 was launched with the Cameo (Chemically Active Material Into Orbit) experiment on a Delta rocket on October 24, 1978. Nimbus 7, the primary payload, is the first satellite equipped to monitor the atmosphere for natural and artificial pollutants. It carries a Total Ozone Mapping Spectrometer (TOMS) instrument which in 1987 discovers the human-made ozone hole over Antarctica. The Cameo experiment studies Earth’s auroral belts. Cameo remains attached to the spent Delta second stage. On this date two trackable pieces detach from the Delta stage-Cameo combination at an altitude of 900 km. Though expected to remain in orbit for years, they decay from orbit within 2 weeks. This high susceptibility to atmospheric drag implies a very large area-to-mass ratio.

John Gabbard, “History of Satellite Breakups in Space,” *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985, pp. 30-39; *Satellite Situation Report*, Project Operations Branch, GSFC, December 31, 1992; letter, Nicholas L. Johnson to Joseph P. Loftus, Jr., JSC, August 17, 1993.

May 29 GSFC notifies McDonnell Douglas Space Systems Company that Delta rockets are exploding in orbit, and asks it to find out why.

July The AIAA Technical Committee on Space Systems produces the first major position paper on the orbital debris problem. It states that "there is. . . no strong national or international concern for space debris management," even though "space debris control needs to be dealt with. . . as a common problem shared by all space users." In its conclusions and recommendations, the document calls the orbital debris problem "real but not severe," though "action to resolve it is imperative," and "no obvious, simplistic resolution is evident." It goes on to say that "continuation of present. . . practices and procedures ensures that the probability of collision. . . will eventually reach unacceptable levels, perhaps within a decade," and that "coordinated action should be taken immediately if the future use of space is not to be severely restricted." Specifically, the position paper calls for

- development of bumpers to shield spacecraft from small debris impact, and evasive capability for avoiding large debris
- immediate action in education, space vehicle design, and operational procedures and practices
- national and international space policies and treaties.

The AIAA position paper concludes by stating that, "corrective action must begin now to forestall the development of a serious problem in the future."

"Space Debris: An AIAA Position Paper," AIAA Technical Committee on Space Systems, July 1981.

July 24 Cosmos 1275, a *Tsikada*-class navigation satellite launched into a 1014-km-by-961-km orbit on June 4, 1981, disintegrates into more than 300 trackable debris pieces at an altitude of 977 km. Only 30 pieces had decayed from orbit on January 1, 1998. The satellite, a 700-kg cylinder 1.3 m in diameter and 1.9 m long, operates within an altitude range populated by a large fraction of the total mass of orbital debris, and at an inclination with a high probability of collision. Intentional destruction is unlikely, as this would endanger the remainder of the satellite constellation of which Cosmos 1275 was a member (at least ten satellites for the *Tsikada*-class). It is believed that Cosmos 1275 carried no pressurized propellant vessels which could explode. Eliminating these explanations leads many analysts to conclude that the breakup was caused by a collision with a piece of orbital debris. Darren McKnight, U.S. Air Force Academy, stated in 1987 that it was impossible to be certain of the cause of the Cosmos 1275 breakup because the Soviets were withholding information. McKnight stated that, "one of the most easily implemented and most useful countermeasure[s to the orbital debris problem] is open exchange of information on space systems." After the breakup of the Soviet Union in 1991, Russian space officials were more forthcoming. They confirmed that collision is also a candidate for the cause of the Cosmos 1275 breakup.

Darren McKnight, "Determining the Cause of a Satellite Fragmentation: A Case Study of the Cosmos 1275 Breakup," *Space Safety and Rescue 1986-1987*, Univelt, Inc., San Diego, pp. 145-163; "A Position Paper on Orbital Debris Compiled by An Ad Hoc Expert Group of the International Astronautical Academy," Committee on Safety, Rescue, and Quality, August 27, 1992.

August 22 The Cosmos 434 satellite was launched into a 261-km-by-194-km orbit at a 51.6-deg inclination on August 12, 1971. After an unusual series of maneuvers it was left in an 11,804-km-by-186-km orbit. The satellite reenters over Australia on this date. To dispel fears that it might carry radioactive materials, the Soviets announce that Cosmos 434 is a "lunar cabin." The Soviet Union used the same term to describe the U.S. Apollo Lunar Module. The announcement helps confirm long-held suspicions that Cosmos 434 was a relic of the failed Soviet manned lunar program.

Dennis Newkirk, *Almanac of Soviet Manned Space Flight*, Gulf Publishing Company, 1990, p. 105.

September 17 A piece of the NOAA 4 Delta second stage which exploded in August 1975 undergoes a secondary breakup, perhaps through collision. Another explanation is that the piece was a small pressure vessel which exploded. It breaks into six pieces too small to catalog.

John Gabbard, "History of Satellite Breakups in Space," *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985, pp. 30-39.

October 6 NASA signs a Memorandum of Agreement formalizing NORAD / ADCOM's commitment to provide collision avoidance support for Shuttle missions. The agreement was in effect informally before the STS-1 launch in April 1981.

Interview, David S. F. Portree with Michael Collins and J. Steven Stich, August 31, 1993; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

1982

End of year launches reaching Earth orbit or beyond (since 1957)	2389
End of year satellites (objects in orbit)	5593

During the year INASAN begins photometric observations of selected Earth-orbiting objects.

Lydia Rykhlova, "Optical Observations in the Geostationary Orbits: Data Reduction" (not dated), Loftus Orbital Debris Files.

January Jeanne Lee Crews establishes the Orbital Debris Impact Laboratory at JSC. Its first project is to study the hypervelocity impact characteristics of composite materials.

Memorandum, Eric Christiansen to David S. F. Portree, "Historical Data on the NASA JSC Hypervelocity Impact Test Facility (HIT-F)," July 2, 1993; Jeanne Lee Crews and Eric Christiansen, " The NASA JSC Hypervelocity Impact Test Facility (HIT-F)," AIAA 92-1640, presented at the AIAA Space Programs and Technologies conference, March 24-27, 1992.

April McDonnell-Douglas Space Systems Company publishes MDC-H0047, *Investigation of Delta Second Stage On-Orbit Explosions*. The company's investigative team concludes that Delta second stage explosions are caused when residual hypergolic propellants mix accidentally. Delta upper stages have a single propellant tank divided by a bulkhead which separates the fuel from the oxidizer (fig. 5). Those in high-inclination, sun-synchronous orbits are especially prone to breakup because they undergo periods of prolonged solar heating, which can overpressurize the propellant tank and eventually rupture the separating bulkhead. Deltas in other orbits explode because the second stage undergoes thermal stresses as it passes in and out of sunlight many times each day. These stresses can crack the bulkhead. The policy of restarting Delta second stages after payload separation to vent oxidizer was established informally in August 1981, when the cause of the explosions was first understood. It is formalized by NASA this year. In 1985 Joseph Loftus briefs the National Space Development Agency of Japan (NASDA) on the Delta problem. NASDA subsequently adopts similar venting policies for its Delta-derived H-1 rockets.

Nicholas L. Johnson and Darren McKnight, *Artificial Space Debris*, revised edition, Orbit Books, 1991.

April 19

The Soviet Union launches the Salyut 7 space station, a near-twin of the Salyut 6 station it replaces. It features improvements to its cosmonaut living facilities, strengthened docking rings, and more efficient solar arrays. In addition, Salyut 7 has transparent plastic covers mounted over several of its portholes to protect them from meteoroids and orbital debris. Of the crews living on Salyut 7, Soyuz T-10B cosmonauts Leonid Kizim, Vladimir Solovyev, and Oleg Atkov spend the most time aloft – a world-record 237 days.

Dennis Newkirk, *The Almanac of Soviet Manned Space Flight*, Gulf Press Company, 1990, pp. 228-230, 255.

June 18

The Soviet Union launches Cosmos 1379 against the Cosmos 1375 target satellite. Intercept occurs at an altitude of 1005 km after two orbits, but Cosmos 1379 fails to explode. The test is part of a 7-hour strategic exercise which also includes six missile launches. It simulates a Soviet nuclear assault on the U.S. and western Europe. After this test, the Soviets impose a moratorium on ASAT tests and urge the U.S. to do the same. U.S. Secretary of Defense Frank Carlucci told the U.S. Congress in 1989 that the Soviet ASAT system was maintained in “a constant state of readiness” in spite of the moratorium.

Nicholas L. Johnson, *The Soviet Year in Space 1988*, Teledyne Brown Engineering, 1989, p. 84; Nicholas L. Johnson, *The Soviet Year in Space 1990*, Teledyne Brown Engineering, 1991, p. 96; Douglas Hart, *The Encyclopedia of Soviet Spacecraft*, Exeter Books. 1987, p. 50-51.

July 2

On mission STS-4 Space Shuttle orbiter Columbia passes within 10 km of the Soviet upper stage which placed the Intercosmos 14 science satellite into orbit. At the time of the conjunction, Columbia is in a 28.5-deg orbit at 324 km, a record altitude for the Shuttle program. The Intercosmos 14 upper stage reached a 1707-km-by-345-km orbit at a 74-deg inclination on December 11, 1975. Within a few months of the conjunction with Columbia the upper stage reenters Earth’s atmosphere.

Letter, Nicholas L. Johnson to Joseph P. Loftus, Jr., August 17, 1993; *Jane’s Spaceflight Directory 1988-89*, Reginald Turnill, editor, Jane’s Information Group, p. 163; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 169.

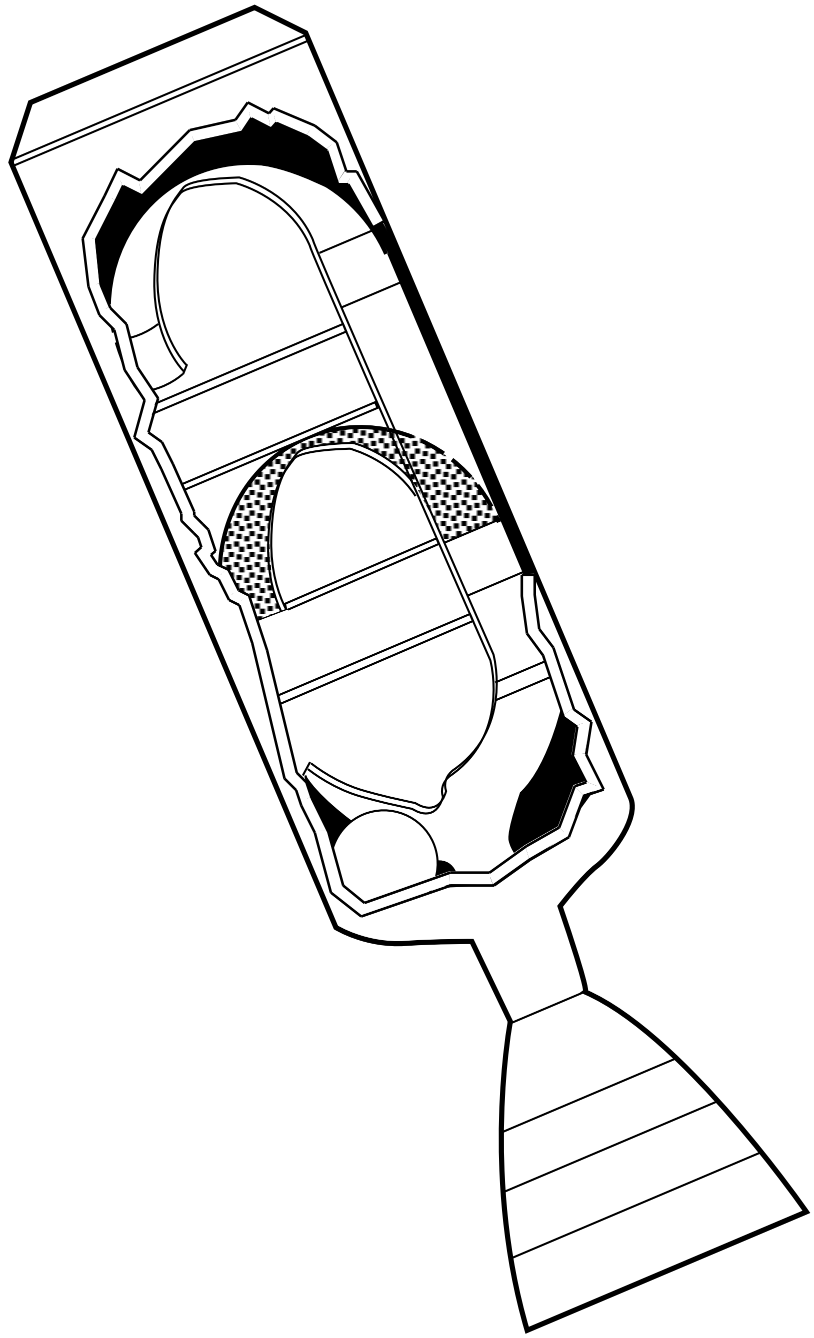

Figure 5.

In this cutaway of the second stage of the Delta launch vehicle, the stippled area is a wall dividing the common propellant tank into oxidizer and fuel sections. The oxidizer and fuel are hypergolic – that is, they ignite on contact. A rupture in the separating wall, possibly caused by corrosion or thermal stresses (repeated expansion and contraction), permits them to mix and ignite, producing an explosion which destroys the stage. Stages left in sun-synchronous orbits seem to be particularly prone to rupture. This may be related to the solar heating pattern they experience, which is different from that experienced by spacecraft at other orbital inclinations. Often hundreds of catalogued pieces result. Chinese Long March 4 upper stages and Soviet/Russian Block DM upper stage ullage motors are of similar design and use hypergolics. They have also undergone on-orbit explosions. Ariane upper stages also have a common propellant tank divided by a wall, but do not use hypergolics. They are thought to break apart because of overpressurization of the propellant tank, possibly through solar heating. Venting the oxidizer remaining in the stage after it reaches its intended orbit can prevent inadvertent explosions.

July 27-29

JSC conducts the first major conference dedicated to the orbital debris problem. More than 100 participants representing NASA Jet Propulsion Laboratory (JPL), GSFC, MSFC, and JSC, the Department of Defense (DoD), Battelle Institute, Lockheed Sunnyvale, ESA, the National Science Foundation, NORAD, Comsat, the Max Planck Institüt in West Germany, and more than 40 other organizations present 37 papers on definition of the debris environment, spacecraft shielding requirements, and space object management (including disposal methods and policy considerations). The workshop recommends that

- The LEO debris environment should be better defined, and sensors should be orbited to gather data in LEO and GEO. One significant result of the conference is, however, a shift in emphasis away from using expensive flight experiments for data gathering, to using less expensive, usually existing, ground-based sensors.

- The costs and effectiveness of orbital debris control methods should be analyzed in detail.

- New operational procedures should include reducing the number of unplanned explosions; using reentry trajectories for planned explosions; using “anti-litter design and operational habits;” and using solar and lunar perturbations to reenter GEO objects.

The workshop showed its participants “for the first time that there was a community of interest” in the orbital debris problem.

Interview, David S. F. Portree with Andrew E. Potter, May 14, 1993; Donald J. Kessler, “Summary of Workshop Activities,” *Orbital Debris* (NASA CP 2360), Donald J. Kessler and Shin-Yi Su, editors, 1985.

Interlude: Orbital Debris and Popular Culture

Space exploration excites much public interest and enthusiasm. It is thus not surprising that orbital debris, like many other space issues, has established itself in popular culture.

Non-technical popular science articles inhabit the marches between technical articles and popular culture entertainment. For the orbital debris researcher they are important public education venues. In 1978 space writer Leonard David published in *Future* magazine the article “Space Junk: It’s Time to Invent Orbital Baggies,” a non-technical piece inspired by the Kessler and Cour-Palais technical article in the *Journal of Geophysical Research.* It was the first popular piece to describe the large uncatalogued debris population. In 1980 Burton Cour-Palais, Donald Kessler, NORAD Civilian Analyst Preston Landry, and Reuben Taylor, a JSC engineer planning on-orbit satellite servicing, collaborated to produce “Collision Avoidance in Space” for *IEEE Spectrum*. In 1982 Kessler published “Junk in Space” in *Natural History* magazine. Jim Shefter, writing for *Popular Science*, approached NORAD for an interview in 1981. Resistance from some then in authority at NORAD (justified later on the grounds that *Popular Science* is not a refereed technical publication) was overruled by the NORAD public affairs office. Shefter’s July 1982 article, “The Growing Peril of Space Debris,” won an important science writing award. It put the orbital debris problem on the cover of the widely-circulated *Popular Science* magazine, helping to raise public awareness. This is, of course, not a complete list of popular audience orbital debris publications – hundreds have been published.

Among the earliest references to the orbital debris problem in popular culture entertainment is a

1982

Donald Duck comic book published in 1963. The “lost-in-space Professor Hermit” fires rocket trash cans into space so he will not litter his planet. Donald Duck and his nephews crash on his planet after their spacecraft collides with one of the professor’s garbage rockets. The message is that scientists should not fire garbage into space without understanding the consequences. Much later (1990), *Pogo* explored the world of orbital debris. “Alien robocoppers” arrive and see humanity’s space junk orbiting the Earth. Owl announces to Churchy the turtle that he plans to build a “space junk junk” from materials gathered at a junkyard and collect orbital debris for disposal in the Sun. Unfortunately, Owl’s Icarus II spaceship explodes. The orbital debris problem is left unsolved.

Science fiction literature is a natural venue for orbital debris speculation. In *Homegoing* (1989), award-winning author/editor Frederik Pohl postulated a future Earth surrounded by “garbage belts” of 90,000 trackable debris pieces. A character trained as an astronaut describes the final attempt to orbit a spaceship with a crew. The craft was destroyed by debris strikes, and her colleagues killed. Previous generations “shot us out of space forever!” she exclaims. Pohl writes that “the thing that keeps the human race trapped on the surface of the Earth is its own previous activities in space. Just as has happened often before in human history, the human race has been defeated by its own success.”

Television has also touched on the orbital debris issue. In the short-lived late 1970s television series *Salvage 1*, Andy Griffith starred as lone entrepreneur who saw potential profit in salvaging disused space hardware. Orbital debris has not yet been a major source of inspiration for feature films. However, at least one orbital debris researcher’s office is graced by a quote from *Star Trek V: The Final Frontier*. A Klingon warship appears near the drifting Pioneer 10 space probe (launched in 1972) and blasts it to pieces. On the bridge, the warship’s captain, bored from a prolonged interstellar peace, declares that, “shooting space garbage is no test of a warrior’s mettle.”

Jim Shefter, “The Growing Peril of Space Debris,” *Popular Science*, July 1982, pp. 48-51; Donald J. Kessler, “Junk in Space,” *Natural History*, Vol. 91, No. 3, March 1992, pp. 12-18; *Walt Disney’s Donald Duck Beyond the Moon*, Gold Key, April 1963; “Pogo,” Los Angeles Times Syndicate, March 6-11, April 16-28, 1990; Leonard David, “Space Junk: It’s Time to Invent Orbital Baggies,” *Future*, November 1978, pp. 68-69; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993; interview, David S. F. Portree with Donald J. Kessler, June 1, 1993; Frederik Pohl, *Homegoing*, Ballantine, 1989; note, Donald J. Kessler to David S. F. Portree September 14, 1993.

October The Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) uses its Experimental Telescope System (ETS) outside Socorro, New Mexico, to record the second-stage burn of a two-stage, solid-fueled Inertial Upper Stage (IUS) in GEO. The ETS is the prototype for the DoD’s Ground-based Electro-Optical Space Surveillance (GEODSS) network. The IUS second-stage burn circularizes and changes the plane of the orbit. The plume of aluminum oxide particles, hundreds of kilometers across, is bright with reflected sunlight. The JSC orbital debris team requests that MIT-LL record an IUS burn scheduled for early 1983 to permit additional study of aluminum oxide particle dispersion.

Donald J. Kessler, “A Partial History of Orbital Debris: A Personal View (Part 2),” *Orbital Debris Monitor*, Vol. 6, No. 4, October 1, 1993.

November The JSC Orbital Debris Impact Laboratory conducts its first hypervelocity impact test. It uses a 1.78-mm two-stage light-gas gun built inhouse using plans provided by Donald Humes at LaRC.

Memorandum, Eric Christiansen to David S. F. Portree, “Historical Data on the NASA JSC Hypervelocity Impact Test Facility (HIT-F),” July 2, 1993; “Hypervelocity Impact Test Facility” brochure, 1991.

1983		
	End of year launches reaching Earth orbit or beyond (since 1957)	2516
	End of year satellites (objects in orbit)	5780

During the year Burton Cour-Palais and Donald Kessler discuss orbital debris with space station planners at JSC and MSFC. Cour-Palais works closely with MSFC, which is designing habitation modules. He asks Kessler to develop an orbital debris reference environment for a space station.

Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 2)," *Orbital Debris Monitor*, Vol. 6, No. 4, October 1, 1993.

During the year The joint U.S.-Dutch-British Infrared Astronomy Satellite (IRAS) images most of the sky in infrared wavelengths, providing data for revolutionary discoveries about our universe. IRAS also detects orbital debris. Data showing debris are discarded as noise. Donald Kessler and Andrew Potter obtain a sample of the noise data and analyze it for signs of orbital debris. Analysis proves to be much more difficult than expected and is abandoned. Analysis of discarded data in the early 1990s by IRAS Space Research Groningen, in the Netherlands, shows that many known orbital debris objects above 3000 km were detected. Two transtages in near-geosynchronous orbits and a geodetic satellite 6000 km high are positively identified in the data. No objects could be detected below the satellite's 900-km orbital altitude or above 300,000 km.

P. R. Wesselius, "Mid-term Review of IRAS Results on Orbital Debris," March 1, 1991; note, Andrew E. Potter to David S. F. Portree, August 2, 1993.

February 7 The Cosmos 1402 RORSAT was launched on August 30, 1982. Normally three pieces are produced when a RORSAT completes its mission. Two pieces remain in LEO and decay quickly, while the third, the nuclear reactor with an attached rocket, boosts to an 800-900-km storage orbit with an estimated lifetime of 300-1000 years. Only two pieces were produced when Cosmos 1402 made ready to send its reactor to storage orbit on December 28, 1982, signifying a separation malfunction which fouled the reactor boost engine. On January 8 the Soviets confirm that Cosmos 1402 carries nuclear fuel. They eject the fuel elements from the reactor vessel. This procedure helps ensure that the fuel elements will burn up during reentry and not strike the ground. On this date the fuel elements reenter over the South Atlantic. No increase in atmospheric radioactivity is detected in the area. The Soviet news agency TASS implies that the satellite performed normally and states that "extraction of the fuel core. . . from the reactor guaranteed its complete incineration." RORSAT launches resume in 1984.

Nicholas L. Johnson, *The Soviet Year in Space 1983*, Teledyne Brown Engineering, 1984, pp. 31-32; *Interavia Space Directory 1992-93*, Andrew E. Wilson, editor, pp. 191-192.

April 5 Space Shuttle Challenger, on its maiden flight (STS-6), deploys the second IUS and the first Tracking and Data Relay Satellite (TDRS). The TDRS series comprises large GEO satellites (17.4 m wide fully deployed) essential to NASA's plans for the Space Shuttle and major LEO facilities, such as the Hubble Space Telescope. Overall cost of the TDRS system was nearly $3 billion by 1985. The IUS first stage performs flawlessly. The MIT-LL ETS records for JSC the second stage burn, which is designed to place TDRS-1 in GEO. Cerro Tololo Inter-American Observatory in Chile also observes the burn. The second stage motor fails, tumbling the satellite and injecting it into a useless orbit (later it is stabilized and maneuvered to a useful GEO position). Joseph Loftus arranges briefings at which NASA, DoD, and contractor officials view the recordings of the normal (October 1982) and failed burns. The size and intensity of the plumes make obvious the huge number of aluminum oxide particles produced in solid rocket motor burns.

Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part Two)," *Orbital Debris Monitor*, Vol. 6, No. 4, October 1, 1993; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

June 18-24

On mission STS-7, Space Shuttle Challenger collides at 5 km / second with a titanium-rich paint chip 0.2 mm across, producing a window pit 4 mm in diameter. The crew notes the pit while still in space, and reports it to the Mission Control Center (MCC) in Houston. Replacing the damaged window costs over $50,000.

Space Program Space Debris: A Potential Threat to Space Station and Shuttle, GAO, April 1990.

July 27

While working aboard the Salyut 7 space station, cosmonauts Alexander Alexandrov and Vladimir Lyakhov have their routine experimental program interrupted by a loud noise. They evacuate to their Soyuz T-9 spaceship, which is docked at the station's rear port. After they return to the station's work compartment, they discover an impact pit 3 mm in diameter in one of the viewports. It is not possible to confirm that this was formed by an orbital debris impact. The Soviets suggest the pit was caused by a meteoroid from the Delta Aquarid shower.

David S. F. Portree, "Soyuz T-8, T-9, and T-10A," *Magill's Survey of Science: Space Exploration Series*, 1988, pp. 1538.

August

Centre National d'Etudes Spatiales (CNES) "reorbits" the French-German Symphonie GEO satellite, raising its orbital altitude to 80 km beyond GEO.

October 18-19

The U.S. Air Force Scientific Advisory Board (SAB) Ad Hoc Committee on Potential Threat to U.S. Satellites by Space Debris meets at the Pentagon in Washington, D.C. In 1984 the SAB publishes a report on the meeting. It states that the smallest object detectable by NORAD radars at 500 km is 4 cm in diameter. At GEO altitude no objects smaller than about 1 m are detectable. The report also comments on the national and international orbital debris policy environments. It maintains that because the "U.S. space community is fragmented from an overall management perspective. . . broad common policies are difficult to implement. Hence, our immediate concern [regarding developing orbital debris policies] should be domestic." It states that the main reason for the lack of coordinated effort on orbital debris on the U.S. national level is a lack of high-level direction. It says the national situation is "a microcosm of the international situation." The SAB report calls for negotiations with the Soviets to set treaty limits on ASAT tests. It recommends that

- NASA and the U.S. Air Force refine their orbital debris environment model by December 1984.

- Interaction between NASA and the ESA be used as a way of fostering international cooperation on orbital debris.

- Spacecraft and launch vehicle manufacturers “undertake prudent measures to reduce future space debris by using techniques such as tethering loose mechanisms, venting spent propellant tanks, and other steps which . . . do not cause significant hardship or cost impact to their designs.”

The report’s recommendations conclude with a call for reappraisal of the orbital debris problem after the recommended measures are implemented, “perhaps in the January-March 1984 time frame.”

Report of the U.S. Air Force Scientific Advisory Board Ad Hoc Committee on Potential Threat to U.S. Satellites Posed by Space Debris, December 1983 (draft copy).

November 3 During EVA outside Salyut 7, cosmonaut Alexander Alexandrov is reprimanded by ground controllers for releasing pieces of trash to watch them drift away. They fear that reflections from the glittering bits of junk will confuse Salyut 7’s orientation sensors.

David S. F. Portree, “Soyuz T-8, T-9, and T-10-A,” *Magill’s Survey of Science: Space Exploration Series*, 1988, pp. 1539.

1984

End of year launches reaching Earth orbit or beyond (since 1957)	2645
End of year satellites (objects in orbit)	5921

During the year ESA moves GEOS 2 to a higher orbit, freeing its slot in GEO for future use.

K. Heftman, “Overview of European Activities on Orbital Debris,” *Orbital Debris: Technical Issues and Future Directions* (NASA CP 10077), Andrew E. Potter, editor, September 1992, pp. 1-7.

During the year The 1984 Commercial Space Launch Act goes through Congress. Section 7 empowers the Secretary of Transportation to license U.S. launches. Section 6(b)(2) gives the DOT limited jurisdiction over foreign payloads launched by U.S. corporations, and over U.S. payloads not subject to regulation by the Federal Communications Commission (FCC) or NOAA, so that they do not “jeopardize the public health and safety, safety of property, or any national security interest or foreign policy interest of the United States.” These sections are later seen as broad enough to mandate DOT regulation of the creation of some types of orbital debris.

Orbital Debris Mitigation Techniques: Technical, Economic, and Legal Aspects, AIAA Special Project Report SP-016-1992.

January In his State of the Union address, President Ronald Reagan calls for NASA to build a space station within a decade.

late January-early February

The MIT-LL uses the ETS to record on videotape orbital debris environment data for NASA. The space agency signed a contract with MIT-LL in late 1983. The ETS is used in staring mode – that is, its telescopes point always toward one place in the sky. Orbiting debris pieces pass through the fields of view of the telescopes. After processing and analysis at JSC, the videotapes show that about 4 fragments per hour were detected. The number expected, based on the NORAD catalog, was only 1.3 fragments per hour. During 2 hours of exceptional sky clarity, the ETS detects 8 objects per hour. Later ETS data, combined with ground-based infrared telescope data and data on debris albedo collected by Karl Henize in 1987-1990, makes clear that the initial ETS tests detected pieces not much smaller than 10 cm. The tests show correctly that there is an uncatalogued debris population potentially more important to spacecraft operations than the catalogued population. They also make clear that the optical orbital debris environment is not adequately understood, leading to the JSC-USSPACECOM GEODSS agreement implemented in 1988.

L. G. Taff, D. E. Beatty, A. J. Yakutis, and P. M. S. Randall, "Low Altitude, One Centimeter Space Debris Search at Lincoln Laboratory's (M.I.T.) Experimental Test System," *Advances in Space Research*, Vol. 5, 1985, pp. 35-45; Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 2)," *Orbital Debris Monitor*, Vol. 6, No. 4, October 1, 1993.

April 6-13

NASA launches the LDEF inside the cargo bay of Space Shuttle Challenger on the STS 41-C mission. Challenger deploys it into a 480-km-by-474-km orbit at 28.5-deg inclination. After its cargo bay is cleared of the 11-ton, bus-sized LDEF, Challenger retrieves the Solar Max satellite. Astronauts James van Hoften and George Nelson perform the first on-orbit satellite repairs in the Shuttle cargo bay. About 1.5 m^2 of thermal blankets and 1 m^2 of louvers from Solar Max are removed and returned to Earth. JSC acquires "every louver with a hole in it." The louvers are excellent debris capture cells, though of course they were not built with that in mind. They are hollow and resemble Whipple Bumpers. The outer surface broke up particles, and the inner surface captured them in molten aluminum. The JSC orbital debris team analyzes the captured particles in the facility which studied the Apollo lunar samples. The Space Science Branch at JSC earlier suggested that a Shuttle might retrieve a disused satellite for analysis, but retrieval of the Solar Max material reduces the need for an old satellite. The idea surfaces again in 1988-89, when NASA and the Strategic Defense Initiative Organization (SDIO) become interested in studying the effects on hardware of long exposure to space conditions. Both organizations plan to build space facilities with lifetimes of decades.

Interview, David S. F. Portree with Andrew E. Potter, May 14, 1993; interview, David S. F. Portree with Donald J. Kessler, June 1, 1993.

May

The PARCS radar observes debris produced by the December 20, 1983, breakup of Cosmos 1405, spotting more than 130 fragments. Conventional NORAD tracking had catalogued only 33.

Nicholas L. Johnson, "History and Consequences of On-Orbit Breakups," *Advances in Space Research*, Vol. 5, 1985, pp. 11-19.

June 25-July 7

The orbital debris workshop at the COSPAR (Committee For Space Research) XXV meeting in Graz, Austria, is the first international workshop dedicated entirely to orbital debris. About 20 researchers from the U.S., Britain, ESA, Czechoslovakia, and West Germany present papers.

Space Debris, Asteroids, and Satellite Orbits, Donald J. Kessler, *et al*, editors, Pergamon Press, 1985; interview, David S. F. Portree with Donald J. Kessler, June 7, 1993.

July

JSC 20001, entitled “Orbital Debris Environment for Space Station,” is published. NASA uses this orbital debris reference environment model for space station design until 1991.

1985

End of year launches reaching Earth orbit or beyond (since 1957)	2766
End of year satellites (objects in orbit)	6665

February

Early this month Soviet ground controllers lose radio contact with the 20-ton Salyut 7 space station. It had been functioning normally with no crew aboard.

April 4

The Governor of the State of Idaho, John V. Evans, signs a proclamation making July 16, 1985, through July 24, 1986, U.S. Space Observation Year, and July 16, 1985, Space Exploration Day. The proclamation states, in part, “we in Idaho encourage those involved in the [space] Program. . . to consider Idaho a place where the problems associated with space debris can be addressed.” Idaho’s interest in space is attributed in the proclamation to its serving as a training area for astronauts and a supplier of metals used in aerospace hardware.

Proclamation, Office of the Governor, State of Idaho, Boise, April 4, 1985.

May 23

George Kovolos, University of Thessaloniki, Greece, logs the last in a series of seven photographs of the young moon at 17:41:50 UT (Universal Time). One photo captures a flash of light near the lunar terminator. Kovolos interprets it as an energetic event on or near the lunar surface – possibly a meteoroid impact, a volcanic eruption, or some kind of ionization phenomenon. In 1989, JSC’s Paul Maley and Richard Rast independently discover that the derelict U.S. military weather satellite DMSP F3 passed 0.25 deg east of the flash location about 80 seconds before Kovolos logged his last photograph. After John Seiradakis supplies better data on Kovolos’ location at the time he photographed the flash, Rast and Maley independently determine that DMSP F3 passed just 2-3 arc minute from the flash location at 17:40:04 UT. Photometry data supplied by USSPACECOM and MIT-LL confirm that sunlight reflects unpredictably off the satellite’s surfaces. Several times in the 1980s astronomers mistook sunlight glinting off satellites for new astronomical phenomena. According to Maley, the potential for harm to the science of astronomy is not known, because very little research into satellite optical phenomena has been conducted.

“Lunar Flash Revisited,” *Sky & Telescope*, June 1990, p. 590; interview, David S. F. Portree with Paul D. Maley, May 14, 1993.

1985

June 6 The Soviets launch the Soyuz T-13 rescue mission to prevent Salyut 7 from undergoing an uncontrolled reentry. They also want to keep the station available to Soviet cosmonauts until after the overdue launch of its successor. Cosmonauts Vladimir Dzhanibekov and Viktor Savinykh perform a perilous manual docking with the slowly tumbling station. They stabilize it, orient its solar arrays toward the Sun, and recharge its batteries. Salyut 7's own orbit-boosting engines were crippled by a line rupture in 1983, so an automated Progress freighter serves as a tugboat to raise Salyut 7's orbit. It also delivers replacement parts for repairs. On October 2, 1985 Cosmos 1686 docks with Salyut 7. The 18-ton spacecraft can serve as a greenhouse, space tug, or laboratory, the Soviets say.

Phillip Clark, *The Soviet Manned Space Program*, Salamander Books, Ltd., 1988, pp. 142-145.

July 29-
August 6 On the STS 51-F mission, the Space Shuttle Challenger carries Spacelab 2, a suite of astronomy instruments. On mission day two, astronaut Karl Henize notices a small red object keeping station with the Shuttle about 3 m above the payload bay. The object is apparently a bit of debris left in the payload bay during prelaunch preparations. A few hours later the object drifts off to become a short-lived, uncatalogued member of the population of 1-cm debris. A few months later Henize, who worked with Fred Whipple on satellite tracking from 1956 to 1959, left the astronaut corps to join the JSC orbital debris team.

Interview, David S. F. Portree with Karl Henize, June 8, 1993.

September 13 A U.S. Air Force F-15 fighter plane launches a small kinetic-energy interceptor at the Solwind (P-78) gamma ray solar physics satellite. USSPACECOM catalogs 285 trackable pieces of debris from this Strategic Defense Initiative (SDI) ASAT test, of which 8 remained in orbit on January 1, 1998.

The Solwind ASAT Test (1985)

Members of the JSC orbital debris team learned of U.S. Air Force plans for the Solwind ASAT test in July 1985. Shin-Yi Su, with Lockheed at JSC, modeled the effects of the test. He determined that debris produced would still be in orbit in the 1990s. It would force NASA to enhance debris shielding for its planned LEO space station.

Earlier the U.S. Air Force and NASA had worked together to develop a Scout-launched target vehicle for ASAT experiments. NASA advised the U.S. Air Force on how to conduct the ASAT test to avoid producing long-lived debris. However, congressional restrictions on ASAT tests intervened. In order to get in an ASAT test before an expected Congressional ban took effect (as it did in October 1985), the Secretary of Defense, Caspar Weinberger, determined to use the existing Solwind astrophysics satellite as a target. Andrew Potter, John Stanley, and Donald Kessler worked with the Department of Defense (DoD) to monitor the test's effects.

After Solwind broke up, the JSC team took two orbital debris telescopes and a reentry radar to Alaska. It was the only U.S. territory from which Solwind pieces were observable. Potter took JSC's Lenzar orbital debris telescope aloft in a Learjet and flew from Anchorage toward Nome. Stanley set up a smaller telescope at Circle Hot Springs on the banks of the Yukon River, and a reentry radar on the North Slope, near Barter Island.

The JSC team assumed torn metal would be bright. Surprisingly, the Solwind pieces turned out to appear so dark as to be almost undetectable. Only two pieces were seen. Kessler remembered how fragments produced by firing a hypervelocity pellet at a scaled-down satellite in a laboratory were dark with what appeared to be soot. The tests were conducted at the U.S. Air Force Arnold Engineering Development Center (AEDC). Potter theorized that the unexpected Solwind darkening was due to carbonization of organic compounds in the target satellite; that is, when the kinetic energy of the projectile became heat energy on impact, the plastics inside Solwind vaporized and condensed on the metal pieces as soot. JSC's Faith Vilas used U.S. Air Force infrared telescopes to show that the pieces were warm with heat absorbed from the Sun. This added weight to the contention that they were dark with soot and not reflective. The pieces decayed quickly from orbit, implying a large area-to-mass ratio.

The Solwind test had three important results. It raised the possibility that the objects optical systems were detecting were large and dark, not small and bright as was generally assumed. This had implications for the calibration of optical and radar orbital debris detection systems. The test also created a baseline event for researchers seeking a characteristic signature of a hypervelocity collision in space. In addition, NASA protests raised DoD awareness of the orbital debris problem. This contributed to more responsible conduct of DoD debris-producing activities, and prepared the way for DoD orbital debris policies.

In the end, the Solwind ASAT test had few consequences for the planned U.S. space station. For economic and political reasons unrelated to orbital debris, station completion was pushed beyond the mid-1990s. More important was the record-high level of solar activity during the 1989-1991 solar maximum. This heated and expanded the atmosphere more than anticipated in 1985, accelerating Solwind debris decay.

Interview, David S. F. Portree with John Stanley, June 21, 1993; interview, David S. F. Portree with Donald J. Kessler, May 11, 1993; Donald J. Kessler, "A Partial History of Orbital Debris: A Personal View (Part 2)," *Orbital Debris Monitor*, Vol. 6, No. 4, October 1, 1993; *Interavia Space Directory 1992-93*, Andrew Wilson, editor, p. 198; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

October 25 The Soviet Union places the first Luch / SDRN spacecraft in GEO at 95 deg east. Each Luch weighs 2.2 tons and measures 16 m wide. The Luch / SDRN satellites are roughly equivalent to those of the NASA TDRS series. Using three transponders, they relay communications and telemetry from orbiting Mir and Soyuz TM spacecraft to ground stations.

November The International Astronomical Union (IAU) holds its 19th General Assembly in New Delhi, India. The IAU unanimously adopts a resolution which notes "with grave concern the. . . contamination of space that adversely affects astronomical observations from the ground and from space." The resolution "maintains that no group has the right to change the Earth's environment. . . without full international study and agreement" and "urges that all national representatives bring this concern to the notice of adhering organizations and space agencies in their countries."

1986		
	End of year launches reaching Earth orbit or beyond (since 1957)	2869
	End of year satellites (objects in orbit)	7226

During the year The Structures Working Group at NASA Headquarters develops Space Station Freedom (SSF) program design requirements for orbital debris. The group consults engineers at MSFC, who are designing the habitation modules, and takes into account the 1984 NASA orbital debris model.

January 28 On mission STS 51-L the Space Shuttle Challenger explodes, killing its crew of seven and grounding the U.S. Space Shuttle fleet for nearly 3 years.

The Space Shuttle and Orbital Debris

The Challenger accident highlighted the dangers of space travel and led to reexamination of NASA's space safety policies, including its policies on orbital debris. Shuttle planners first considered the implications of orbital debris for the Space Shuttle before STS-1 flew in April 1981. NORAD agreed to provide the Mission Operations Directorate (MOD) at JSC with data on Shuttle conjunctions with space objects. MOD deferred creating a Flight Rule on orbital debris avoidance, however, in favor of making flight directors responsible for deciding orbital debris avoidance actions on a case-by-case basis.

After the Challenger accident, MOD developed Shuttle Flight Rule 4-61, which stated that an avoidance maneuver would be called for "if a predicted miss distance is less than 2 km radially [below or above the of the orbiter's track], 5 km downtrack [ahead or behind], and 2 km out-of-plane [to either side] and if the maneuver does not compromise either primary payload or mission objectives." This 2-km-by-5-km-by-2-km area around the orbiter is called the maneuver box, or collision avoidance box.

Implementation of Flight Rule 4-61 begins when the MCC Flight Dynamics Officer (FDO) provides orbiter trajectory data to USSPACECOM. This is done several times each day during a mission and before and after each orbiter burn. USSPACECOM then runs a Computation of Misses Between Orbits (COMBO) analysis program using the data supplied by the FDO. Within 1 hour of the FDO sending data to USSPACECOM, the COMBO analysis results reach the MCC. Objects within a 5-km radial, 25-km downtrack, and 5-km out-of-plane alert box are flagged. USSPACECOM continues tracking any risk objects to refine the accuracy of the estimate of their locations. Updates are sent to the MCC so the FDO can model the conjunction. If the conjunction falls inside the alert box a maneuver is not called for, but if it falls "inside of the 2-km radial, 5-km downtrack, 2-km out-of-plane maneuver box, a maneuver will be considered per the flight rule."

MOD determined that because the chance of collision is small, "compromising either primary payload or mission objectives cannot be justified. However, if there are no perturbations to. . . mission objectives, it is best to maneuver for any conjunction with a greater than 1 in 100,000 chance of collision." Flight Rule 4-61 goes on to state that "an acceptable risk of 1 in 100,000 is based on. . . the level of risk taken by other space shuttle elements. The [2 km-by-5-km-by-2 km] ellipsoid stated in the rule guarantees this risk."

Prior to STS-26 in September 1988, it was predicted that an avoidance maneuver would be called for once in every 10 Shuttle flights. This estimate has proven reliable – for example, twice in the 31 Shuttle flights after the Challenger accident (STS-26 through STS-57) objects intruded on the 2-km-by-5-km-by-2-km maneuver box. MCC conducted three avoidance maneuvers and modified operations slightly once to avoid debris. Only one of the maneuvers was prompted by an intrusion into the maneuver box. No avoidance maneuver was carried out for the other maneuver box intrusion, as per the portion of Flight Rule 4-61 permitting the rule to be waived if collision avoidance impinges on mission objectives.

Flight Rule 4-3, "Orbit Conjunctions and Conflicts," also relates to orbital debris. It states, in part, that if COMBO analysis "predicts an on-orbit conjunction within 5 km in the radial and out-of-plane directions and 15 km in the downtrack direction during the first 4 hours of a nominal mission, launch will be held until the next even minute to assure clearance."

"NASA Johnson Space Center Flight Rules," Flight Rule 4-3, 1/20/89, p. 4-3 and Flight Rule 4-61, 4/16/92, p. 4-40; interview, David S. F. Portree with Michael F. Collins, Chief, Trajectory Operations Branch, Flight Design Dynamics Division, JSC MOD, and J. Steven Stich, Rendezvous Flight Dynamics Officer, Trajectory Operations Branch, Flight Design Dynamics Division, JSC MOD, August 17, 1993; J. Steven Stich, "STS Collision Avoidance Procedures" (presentation materials), January 17, 1992, p. 8.

February 20 The Soviet Union launches the Mir space station base block. The Kvant astrophysics module is added to its rear port in April 1987. The Kvant-2 module arrives at Mir in December 1989. The Kristall module is placed opposite Kvant-2 in June 1990, creating a T-shaped space station complex with a mass of about 80 tons. In early 1993 Mir was about 30 m wide across its solar arrays. It revolves about Earth in a 51.6-deg orbit 300-400 km high. Mir is almost always inhabited by two or three cosmonauts. Visiting Shuttle crews have swelled its population to ten.

May 12-13 The U.S. Air Force SAB begins work on a report on the implications of orbital debris for future U.S. Air Force space activities.

June Karl Henize and Faith Vilas take JSC's Lenzar telescope to Oregon to observe Solwind debris. They detect fewer than 10 pieces.

Interview, David S. F. Portree with Karl Henize, June 8, 1993.

June 30-July 12 At the COSPAR XXVI conference in Toulouse, France, JSC researchers present a paper in which they state that at least 30 percent of the material captured from space by a Solar Max thermal blanket comprises micrometeorites. The majority of the particles found are, however, orbital debris – mostly paint chips and aluminum particles.

Franz J. M. Rietmeijer, *et al*, "The Main Electronics Box Thermal Blanket of the Solar Maximum Mission Satellite as an Inadvertent Capture Cell for Orbital Debris and Micrometeorites," abstract in *Scientific and Technical Papers Presented or Published by JSC Authors in 1986* (NASA TM 100457), July 1987, p. 113.

August Harlan Smith, Director of the University of Texas McDonald Observatory, proposes "the ultimate ground-based optical detector of space debris." It consists of two 8-m f/4.3 Cassegrain telescopes 100 m apart. Computers to analyze the mountain of data collected by the telescopes would cost $12 million. Theoretically, the system could detect objects as small as 1 mm. It is ultimately killed by its cost, which is estimated at $100 million.

Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper).

August

Researchers at the Space Telescope Science Institute publish a study of the probability that satellites, including orbital debris, will collide with the Hubble Space Telescope (HST). They conclude that a 5-mm object will strike HST once in 17 years. A strike on the 40 percent of HST comprising solar arrays will cause little damage. A strike elsewhere could destroy the mission or pass unnoticed, depending on the criticality of the component struck. The researchers note that HST's Fine Guidance Sensors had to be designed so they would not track on satellites and lose guide star lock. They warn that light trails from satellites will appear in many of the images from HST and future orbiting instruments.

Michael Shara and Mark D. Johnston, "Artificial Earth Satellites Crossing the Fields of View of, and Colliding With, Orbiting Space Telescopes," *Publications of the Astronomical Society of the Pacific*, Vol. 98, August 1986, pp. 814-820.

September 5

SDIO conducts the Delta 180 test in orbit over Kwajalein Atoll in the Pacific. An SDI satellite carrying an explosive is placed on a collision course with an instrumented Delta second stage. They collide at 10,450 km / hour, and both vehicles are completely destroyed. Although several hundred pieces are observed by ground radar, only 18 debris pieces are eventually catalogued. The test is conducted at an altitude of 192 km to ensure rapid reentry of its products. Half of the pieces reenter within an hour – most of the remainder follow within a few days. One of the reasons Delta 180 is significant is that it is the first U.S. debris-producing test in which orbital debris is taken into account. Lt. Gen. James Abrahamson, head of the SDIO, was NASA Associate Administrator for Space Flight when the TDRS-1 IUS failed in 1983. He was present at the briefings Joseph Loftus arranged at JSC at which tapes of the first two IUS second stage burns were shown. In 1984 Abrahamson became Director of the SDIO, where he heard NASA's concerns about the 1985 Solwind ASAT test. Abrahamson directed that the Delta 180 test be conducted so as not to add to the amount of debris in orbit. Before the test the Delta 180 experiment design team consulted with Donald Kessler on orbital debris lifetimes. After the test Kessler joins Andrew Potter and Eugene Stansbery, a radar expert at JSC, in a measurement campaign coordinated by John Stanley. The campaign uses the Air Force Maui Optical Site (AMOS), GEODSS, and other sensors. Nicholas Johnson, Advisory Scientist at Teledyne Brown Engineering, testified in 1988 to the House of Representatives Subcommittee on Space Science and Applications that the test was "an excellent example of responsible planning of a debris-generating experiment in space."

Interavia Space Directory 1992-93, Andrew Wilson, editor, p. 220; interview, David S. F. Portree with John Stanley, June 21, 1993; *Orbital Space Debris, Hearing before the Subcommittee on Space Science and Applications, Committee on Science, Space, and Technology, House of Representatives*, July 13, 1988, p. 81; note, Andrew E. Potter to David S. F. Portree, July 24, 1993.

October 9

Thomas W. Inman of MSFC publishes a paper titled "Analysis of Orbital Debris Collision Probabilities for Space Station." He applies to SSF the probabilistic approach to assessing potential orbital debris collision hazards used by James McCarter in 1971-72. Inman starts with a catalogued population of 6409 objects in August 1986. He assumes a 7.5 percent average annual growth rate for the catalogued population. He states that the catalogued debris population will number 16,311 by the year 2000 and 48,262 by 2015. Inman updates McCarter's approach by assuming a large population of uncatalogued objects smaller than 4 cm, but larger than 1 mm. Based on models by Donald Kessler, Vladimir Chobotov, and others, Inman assumes that the uncatalogued population is five times the size of the catalogued – 32,045 objects in 1986. Again using a 7.5 percent annual growth rate, this yields an uncatalogued population of 81,555 in 2000 and 241,310 in 2015. The space station selected for analysis is a large dual-keel design with four habitable modules. A collision occurs when an object intrudes on the 85-m radius sphere enclosing the station. The collision probability is also computed for a 19-m radius sphere enclosing the four modules. The station is assumed to be in a 28.5-deg inclination orbit 250-500 km high. Inman finds that for the 85-m sphere the probability of a collision with a catalogued object is already significant in 1986 – about 0.3 at an altitude of 500 km. Uncatalogued objects naturally increase the collision probability. The hazard to the habitable modules is not significant, but "if present growth rates of orbital debris continue, this can be expected to change," Inman states. He concludes by calling for NASA to give high priority to hypervelocity impact testing.

Thomas Inman, "Analysis of Orbital Debris Collision Probabilities for Space Station," October 9, 1986.

November 13 On February 22, 1986, an ESA Ariane 1 launch vehicle carried the French SPOT 1 commercial remote sensing satellite and Swedish Viking astrophysics satellite into orbit. This was the 16th flight (V16) of an Ariane rocket. Its third stage was left in a 835-km-by-829-km orbit at a 98.7-deg inclination (sun-synchronous). On this date the third stage explodes over east Africa, producing a debris cloud immediately detected by the U.S. FPS-79 radar in Pirinclik, Turkey.

Nicholas L. Johnson, "Preliminary Analysis of the Fragmentation of the Spot 1 Ariane Third Stage," *Orbital Debris from Upper-Stage Breakup*, Joseph P. Loftus, Jr., editor, 1989, pp. 41-106; interview, David S. F. Portree with Donald J. Kessler, June 1, 1993.

November 14 The Ariane V16 third stage debris cloud passes over the U.S. for the first time 8 hours after breakup. It passes through the coverage of the FPS-85 missile early warning radar at Eglin Air Force Base in Florida. The FPS-85 detects 44 debris pieces. They orbit at 550-1300-km altitude and have orbital periods of 98-107 minutes. Within hours Nicholas Johnson informs Donald Kessler of the breakup. He passes word to Joseph Loftus, who informs NASA Headquarters. At a meeting already scheduled for this date, NASA Administrator James Fletcher informs ESA Director-General Reimar Lüst of the Ariane breakup.

Ibid.

November 18 Ninety-three trackable pieces are associated with the Ariane V16 breakup.

Ibid.

November 30 Catalogued pieces associated with the Ariane V16 breakup number 274 by this date.

Ibid.

1987		
	End of year launches reaching Earth orbit or beyond (since 1957)	2979
	End of year satellites (objects in orbit)	7430

During the year Darren McKnight, U.S. Air Force Academy, and Nicholas Johnson, Teledyne Brown Engineering, publish *Artificial Space Debris*, the first book devoted to orbital debris. A revised and updated edition is published in 1991.

During the year Gamma ray astronomy instruments carried by the Japanese Ginga (Astro-3) satellite, Solar Max, and instrumented balloons adrift in Earth's upper atmosphere suffer from interference from anomalous gamma ray sources. In 1988 it is revealed that Soviet RORSAT reactors are the sources of the interference. During its 9 years in orbit, Solar Max suffers interference from 18 RORSAT reactors.

Interavia Space Directory 1992-93, Andrew Wilson, editor, p. 117.

January 5-16 Andrew Potter, Karl Henize, and Jerry Winkler use JSC's Lenzar telescope to study the albedo of Ariane V16 debris swarm at the U.S. Naval Observatory's Black Birch facility on the South Island of New Zealand. They look at debris from the Landsat 1 and 3 Delta second stages and Cosmos 1275 satellite for comparison. Faith Vilas and John Stanley use infrared sensors in Hawaii. They find that the Ariane pieces are brighter than average, and that there are significant albedo differences between debris swarms. There is no readily apparent correlation between probable breakup cause and swarm albedo. In general, most debris pieces are very dark, with an average reflectivity of about 0.1 (much darker than the widely-accepted value of 0.5).

Ibid; interview, David S. F. Portree with Karl Henize, June 8, 1993; Karl G. Henize, *et al*, "Optical Properties of Orbital Debris" (AIAA 93-1062), presented at the 31st Aerospace Sciences Meeting & Exhibit, Reno, Nevada, January 11-14, 1993.

February 4 The DoD issues its first official orbital debris policy. It states that the "DoD will seek to minimize the impact of space debris on its military operations. Design and operations of DoD space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements." DoD Assistant Deputy Under Secretary for Policy Philip Kunsberg told the House Subcommittee on Space Science and Applications in 1988 that "the DoD space policy. . . broke new ground by expressly addressing space debris as a factor in planning military space operations." He continued, saying "this does not mean we will curtail or avoid space activities that are necessary for our national security."

Orbital Space Debris, Hearing before the Subcommittee on Space Science and Applications, Committee on Science, Space, and Technology, House of Representatives, July 13, 1988, p. 24.

mid-February Four hundred and sixty-five trackable debris pieces are associated with the November 13, 1986, Ariane V16 breakup. They form a 30-deg-wide ring around the Earth inclined 98.7 deg to the equator, and range in altitude from 500-1400 km. The ring expands in width at 10 deg per month. By this time it was abundantly clear that the Ariane V16 breakup was the worst known orbital debris-producing event in history. Robert Culp, Director of the

Colorado Center for Astrophysics Research, estimated the explosion produced "over 500 trackable debris pieces. . . and an estimated 5000 pieces of debris capable of destroying a spacecraft." In testimony to the U.S. House Subcommittee on Space Science and Applications in 1988, Nicholas Johnson, Advisory Scientist at Teledyne Brown Engineering, estimated that this single explosion increased the debris population by 7 percent.

> *Ibid*; Nicholas L. Johnson, "Preliminary Analysis of the Fragmentation of the Spot 1 Ariane Third Stage," *Orbital Debris from Upper-Stage Breakup*, Joseph P. Loftus, Jr., editor, pp. 41-106.

April 14 The last trackable piece produced by the September 1986 Delta 180 experiment decays from orbit.

May 8 ESA organizes its Space Debris Working Group. Dietrich Rex, Director of the Institüt für Raumflugtechnik und Reaktortechnik (IfRR) of the Technische Universität Braunschweig (TUBS), is made chair.

May 14-15 In the wake of the Ariane V16 breakup, JSC holds the Upper Stage Breakup Conference. NASA shares with ESA the operational procedures it developed after it realized the hazard posed by unvented Delta second stages. NASA and ESA begin holding regular orbital debris coordination meetings.

June James Fletcher tells the NASA Headquarters Office of Space Flight (OSF) to develop a strategy for dealing with orbital debris.

June Karl Henize conducts the first of six annual 2-week orbital debris observing sessions at the Rattlesnake Mountain Observatory of Battelle Pacific Northwest Laboratories. One purpose of the sessions is to determine a mean albedo of orbital debris objects, which can be used to determine the sizes of uncatalogued objects detected by the GEODSS telescopes.

> Interview, David S. F. Portree with Karl Henize, June 8, 1993; note, Andrew E. Potter to David S. F. Portree, August 3, 1993.

July 14 Darrell Branscombe, NASA Headquarters Shuttle Program Office, briefs James Fletcher on a proposal to establish a coordinated NASA orbital debris program. Donald Kessler and Andrew Potter laid groundwork by briefing NASA Headquarters senior staff. A central issue is the need for a ground radar which can sample the 1-cm debris environment. Fletcher agrees to the orbital debris program proposal. He directs Robert Aller, Associate Administrator for Tracking and Data Acquisition, to have radar experts at JPL study the cost and feasibility of the radar. It becomes known as the Debris Environment Characterization Radar (DECR).

> Interview, David S. F. Portree with John Stanley, June 21, 1993; interview, David S. F. Portree with Donald J. Kessler, June 7, 1993; note, Andrew E. Potter to David S. F. Portree, July 24, 1993.

September 19 Israel becomes the eighth country to launch its own satellite. The Offeq-1 satellite is placed into a 1150-km-by-250-km orbit at a 142.9-deg inclination (retrograde). It decays from orbit on January 14, 1989.

1987

October 22 Joseph Loftus and Andrew Potter meet ESA representatives in Rolleboise, France, to exchange information on orbital debris activities. This is the first in what become regular semi-annual ESA-NASA orbital debris coordination meetings. They are held alternately in the U.S. and Europe. The Rolleboise meeting is held concurrently with a meeting of the AIAA Space Transportation Technical Committee, of which Loftus is chair.

December The U.S. Air Force SAB releases *Current and Potential Technology to Protect Air Force Space Missions from Current and Future Debris*, the first important report on orbital debris from a military perspective. It is a follow-up of the 1983 study. According to the report, renewed attention to the orbital debris issue is required because of SDI ASAT testing, SSF, and the projected large increase in the number, weight, and type of spacecraft to be deployed as part of SDI. In its conclusions, the report states that debris is already an important design consideration for large, long-duration space vehicles. It adds that future traffic models range from constrained, which would double the mass in orbit below 2000-km altitude (estimated at 2 million kg in 1987), to the SDI traffic model, which would multiply the mass by 15 times. The report contends that debris management will require international cooperation and agreements, but recommends that the U.S. proceed unilaterally until these agreements can be put in place. The report also recommends that

- The U.S. Air Force, NASA, and the Department of Commerce should join forces to establish specifications and design practices to minimize production of orbital debris.

- The U.S. should take the lead in establishing an international commission on orbital debris to encourage cooperation and exchange of data on the debris environment, and to implement agreed-upon specifications and design practices for future space systems. The U.S. should also foster international cooperation in dealing with hazardous events and in providing satellite collision warnings.

- The U.S. should establish guidelines for ASAT and other space weapons systems to minimize production of long-lived orbital debris.

- Operational U.S. space tracking systems should be alerted to debris-producing events, and should be tasked to provide special monitoring and services when debris-producing events occur.

- New concepts and technology should be developed by 2000 to protect U.S. Air Force space assets from debris.

As a general recommendation, the report calls for more attention to the debris problem from all organizations which operate in space.

Report on Orbital Debris, U.S. Air Force Scientific Advisory Board, December 1987; Ross T. McNutt, *Orbiting Space Debris: Dangers, Measurement, and Mitigation*, Phillips Laboratory, Directorate of Geophysics, Air Force Systems Command, Hanscom AFB, June 1, 1992.

Late in the year

JPL proposes building the QUICKSAT orbital debris research satellite. It would operate in sun-synchronous orbit 500 km above Earth's terminator. The satellite would image debris in stereo using two telescopic cameras. It would keep the Sun behind it so debris pieces would be imaged fully lit. Debris particles as small as 1 mm would be visible up to at least 6 km away. The name QUICKSAT comes from the need to ready the spacecraft for a late 1989 launch, to take advantage of a surplus U.S. Air Force Atlas E rocket. QUICKSAT is not approved, in part because it would cost $100 million, plus $5 million annually for operations.

Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper); interview, David S. F. Portree with Donald J. Kessler, June 7, 1993.

1988		
	End of year launches reaching Earth orbit or beyond (since 1957)	3095
	End of year satellites (objects in orbit)	7245*

*The decline since 1987 was caused by record-high levels of solar activity during the 1988-1991 solar maximum period.

During the year

Donald Kessler works with Jeff Anderson of MSFC to update the 1984 orbital debris model. The update takes into account new data from Solar Max analyses and telescopic measurements which indicate that debris is darker, and thus larger, than in the 1984 model. It depicts a debris environment approximately eight times more severe than that described in 1984.

During the year

John Stanley and his colleagues begin implementing an agreement with the U.S. Air Force for optical monitoring of orbital debris using the GEODSS telescopes on Diego Garcia and Maui. The GEODSS sites collect data in vertical staring mode before dawn and after dusk each clear day at the two sites through 1991, then at the Diego Garcia site alone.

Interview, David S. F. Portree with John Stanley, June 21, 1993.

February 11

The orbital debris issue reaches the White House. President Reagan issues the National Directive on Space Policy, which contains the first U.S. national policy statement on orbital debris. The policy uses much the same language as the February 4, 1987, DoD orbital debris policy. It states that "All space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements. . ." At the insistence of the Office of Management and Budget, it adds the caveat ". . .and cost effectiveness." In its implementation instructions, the Directive calls for the National Security Council to establish the Interagency Group (IG) (Space) to draw together many Federal agencies for consideration of orbital debris issues. The 1989 final revision adds the statement, "The United States government will encourage other spacefaring nations to adopt policies and procedures aimed at debris minimization." E. Lee Tilton, III, Chair of the Orbital Debris Committee at NASA Headquarters, inserted this reference to the orbital debris problem into the President's Space Policy Directive.

Nicholas L. Johnson and Darren McKnight, *Artificial Space Debris*, revised edition, Orbit Books, 1991; interview, David S. F. Portree with Andrew E. Potter, May 14, 1993; interview, David S. F. Portree with E. Lee Tilton, III, August 23, 1993.

February 24

The orbital debris team at JSC details the requirements for the DECR radar system, which will "collect statistical data on orbital debris down to a size of 1 cm or smaller diameter at an altitude of 500 km." DECR would be the first radar specifically designed for orbital debris research. It would draw on lessons learned during a decade of debris detection using tracking radars. DECR would not track (using a "non-tracking radar simplifies the design and resources requirements," the document states), and would have "a narrow radiation pattern, which would, ideally, be directed vertically. . . [and] would be stationary and let debris particles pass through the beam." The document contains reports from JSC, Lockheed, Battelle, and Teledyne Brown Engineering dated from May 1987 through January 1988.

"Debris Environment Characterization Radar Design Studies" (JSC 22827), February 24, 1988.

March

The U.S. Air Force cancels its program to develop kinetic-energy interceptor ASATs launched by F-15 fighter planes in the face of on-going Congressional opposition to ASAT testing. In the course of testing, four ASATs were launched against points in space, one with only partial success. The third test, in 1985, destroyed the Solwind satellite. The last test occurred in October 1986.

April 1

The first issue of *The Orbital Debris Monitor* is published. The quarterly publication is the first dedicated to orbital debris. Its editor is Darren McKnight.

May

This month a particle blasts a crater in the outer pane of a two-pane Mir base block viewport. The crater is surrounded by cracks up to 3 mm long. The damage area is 6-8 mm across. The Soviets assume the impactor was a piece of orbital debris.

Interavia Space Directory 1992-1993, Andrew Wilson, editor, p. 183; Nicholas L. Johnson, *The Soviet Year in Space 1990*, Teledyne Brown Engineering, 1991.

May

The Office of Commercial Space Transportation (OCST) of the DOT publishes *Hazard Analysis of Commercial Space Transportation*, a three-volume report prepared by the Transportation Systems Center in Cambridge, Massachusetts. Chapter 6 of Volume 2 deals with orbital debris hazards. The OCST issues the report because the Commercial Space Launch Act of 1984 calls for it to "promulgate and enforce appropriate safety criteria and regulatory requirements for licensing the commercial space industry."

Hazard Analysis of Space Transportation, OCST, DOT, May 1988.

May 13 TASS announces that radio contact has been lost with the Cosmos 1900 RORSAT. In 1989 the Soviets reveal that contact was lost on April 9. On April 13 Cosmos 1900 ignored a command to boost its reactor to a higher storage orbit.

Nicholas L. Johnson, *The Soviet Year in Space 1988*, Teledyne Brown Engineering, 1989, pp. 72-77.

May 17-19 The Environmental Aspects of Activities in Outer Space Workshop is held in Cologne, West Germany. It is an interdisciplinary meeting on orbital debris and related issues attended by lawyers, scientists, and engineers.

June 30-July 2 JPL uses the 300-m Arecibo radio telescope in Puerto Rico to test the concept of statistically monitoring orbital debris with a radar in a vertical staring mode. Andrew Potter suggested the test to Robert Aller. The test is designed to provide data to support development and construction of the DECR. It provides data consistent with Kessler's estimates of the population of 1-cm debris. Fifteen 1-cm pieces per day pass through the 2-arc-min main beam – Kessler predicted 13 pieces. However, the beam pattern is not well understood, reducing the utility of the experiment.

Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, "The History of Orbital Debris," 1990 (unpublished draft paper); interview, David S. F. Portree with Donald J. Kessler, May 17, 1993; note, Andrew E. Potter to David S. F. Portree, July 24, 1993.

July 13 The Subcommittee on Space Science and Applications of the U.S. House of Representatives Committee on Science, Space, and Technology holds a hearing on the orbital debris problem.

The 1988 Congressional Hearing on Orbital Debris

Before 1988, interest in orbital debris outside the DoD and NASA was intermittent. After President Reagan mentioned the problem in his National Directive on Space Policy, however, many Federal agencies developed sustained interest in orbital debris.

The Subcommittee on Space Science and Applications hearing of July 13, 1988, provides a good overview of the state of orbital debris awareness at the time. It also gives insights into the orbital debris concerns of different parts of the U.S. government. The Subcommittee heard testimony from Joseph B. Mahon, Deputy Associate Administrator for Flight Systems in the NASA OSF; Philip Kunsberg, Assistant Deputy Under Secretary for Policy, DoD; Michael A. Michaud, Director of the Office of Advanced Technology, Department of State; S. Neil Hosenball, former NASA General Counsel and former NASA delegate to the U.N. COPUOS; and Nicholas Johnson, author of books and articles on the orbital debris problem and Advisory Scientist for Teledyne Brown Engineering.

Mahon summarized NASA's three-thrust debris strategy. The technical thrust, he said, involved developing mathematical models and maintaining a database to characterize the orbital debris environment. The measurements thrust involved developing a special orbital debris radar (the JPL DECR) to detect objects in the 1-10-cm range in time for the SSF Critical Design Review (CDR) in mid-1991. According to Mahon, "a firm requirement to protect the station against a future orbital debris hazard has been documented." The policy thrust involved "devising management options for orbital debris prevention, protection, and possible elimination." "NASA has already taken concrete steps to reduce the amount of debris in space. . . the most significant has been the NASA requirement in force since 1982 which established the procedure for Delta upper stages of venting the unspent propellants and gases to prevent an explosion of the Delta upper stage," Mahon added. He also cited establishment of the NASA-ESA Working Group, which developed from joint NASA-ESA efforts to apply NASA's experience with Delta breakups to Ariane.

Philip Kunsberg reported that PARCS radar tests indicated a debris population 7-35 percent larger than that catalogued. He stated that study of returned surfaces from the Solar Maximum Mission satellite indicated the possibility of billions of small debris particles, each about 0.1 mm in size, in LEO. Kunsberg echoed the February 4, 1987, DoD orbital debris policy when he declared that, "while we cannot solve the problem of space debris without the cooperation of other nations, the United States, in the meantime, should address the problem as a nation, both to protect our spacecraft and ameliorate the problem as much as possible."

Michael A. Michaud stated that Soviet Foreign Minister Edvard Schevardnadze had said in May 1988 that space "pollution" needed to be prevented. He declared that the State Department saw "space debris as an inherently international issue. Orbital debris does not observe national boundaries. . . we are all in this together. Sooner or later we need to consult with others." S. Neil Hosenball also described international orbital debris policy. He stated that two international treaties are relevant to the orbital debris problem – the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space (the Outer Space Treaty), and the 1972 Convention on International Liability for Damage Caused by Space Objects (the Liability Convention). (For detailed descriptions, see *Laws for Orbital Debris: The U.N. Space Treaties of 1967 and 1972*, page 15).

Nicholas Johnson then provided an overview of the orbital debris technical issues. He reported that only 5 percent of the artificial objects in space are operational spacecraft. In the year prior to his testimony, he stated, seven Soviet spacecraft had undergone high-intensity explosions. Johnson also stated that less than 20 percent of the human-made objects in space were catalogued.

Orbital Space Debris, Hearing Before the Subcommittee on Space Science and Applications, Committee on Science, Space, and Technology, U.S. House of Representatives, July 13, 1988.

September 29-October 3

Discovery deploys a TDRS during STS-26, the first Shuttle mission since the loss of Challenger in January 1986. USSPACECOM detects an orbital debris object in the Shuttle's 5 km-by-25-km-by-5-km alert box. It does not enter the 2 km-by-5-km-by-2-km maneuver box, so the MCC takes no action.

J. Steven Stich, "STS Collision Avoidance Procedures" (presentation materials), January 17, 1992, p. 10.

September 30

The Cosmos 1900 RORSAT continued its uncontrolled decay over the summer. In mid-September the Soviet Union gave the International Atomic Energy Agency of the U.N. a complete inventory of the reactor's contents in anticipation of a large-scale release of radioactive material. On this date Cosmos 1900 unexpectedly depletes its attitude control propellant. An automatic safety system activates which blasts the reactor, with its 31 kg of enriched uranium fuel, to a 763-km-by-695-km storage orbit. The main body of the satellite reenters over the Indian Ocean the next day. TASS announces that the Soviet Union will continue to launch RORSATs. As of July 1, 1993, however, no new RORSATs had been launched.

Nicholas L. Johnson, *The Soviet Year in Space 1990*, Teledyne Brown Engineering, 1988, p. 77.

November The ESA Space Debris Working Group publishes the report *Space Debris.* In his preface, Professor Reimar Lüst, Director General of ESA, states that the report aims to increase public awareness of the threat to the near-Earth environment posed by orbital debris. He also says that by our failure "to take preventative measures, future generations will inherit an ominous legacy." Dietrich Rex told the University of Chicago Preservation of Near-Earth Space for Future Generations symposium that "by the European report it became clear that Europe heavily depended on U.S. knowledge and data in the space debris field and that increased European activities should be initiated." The Space Debris Working Group was succeeded by the ESA Space Debris Advisory Group and the Space Debris Coordination and Technical Analysis Group after it released this report.

Space Debris: A Report from the ESA Space Debris Working Group, European Space Agency, 1988; Dietrich Rex, "The Current and Future Space Debris Environment as Assessed in Europe," presented at the Preservation of Near-Earth Space for Future Generations symposium, University of Chicago, June 24-26, 1992.

November Gautam Badhwar, with other JSC researchers, develops a method for determining the probable cause of breakups using data on orbital plane change angles and the radar cross sections of pieces produced. Application of this method to breakups of uncertain cause reveals that several breakups thought to have been caused by exploding propellants could have been caused by collisions.

Gautam Badhwar, *et al*, "Characteristics of Satellite Breakups from Radar Cross Section and Plane Change Angle," *Journal of Spacecraft and Rockets*, Vol. 25, 1988, pp. 420-426.

December 2-6 STS-27 is a DoD Shuttle mission. Four orbital debris objects enter the 5-km-by-25-km-by-5-km alert box, and one enters the 2-km-by-5-km-by-2-km maneuver box. As permitted in Flight Rule 4-61, the MCC waives the maneuver requirement, because maneuvering would impact mission objectives.

J. Steven Stich, "STS Collision Avoidance Procedures" (presentation materials), January 17, 1992, p. 10.

1989

End of year launches reaching Earth orbit or beyond (since 1957)	3196
End of year satellites (objects in orbit)	6726*

*The decline since 1988 was caused by record-high levels of solar activity during the 1988-1991 solar maximum period.

During the year The ESA Council approves the Resolution on the Agency's Policy vis-a-vis the Space Debris Issue, based on the findings and recommendations of the ESA Space Debris Working Group.

K. Heftman, "Overview of European Activities on Orbital Debris," *Orbital Debris: Technical Issues and Future Directions* (NASA CP 10077), Andrew E. Potter, editor, September 1992, pp. 1-7.

1989

January At JSC Gautam Badhwar and Phillip Anz-Meador develop a means of calculating the mass of a debris object based on its radar cross section and the changes in its orbital elements caused by atmospheric drag. They find that the mass distribution differs according to the type of breakup, providing a new clue to determining breakup causes.

Gautam Badhwar and Phillip Anz-Meador, "Determination of Area and Mass Distribution of Orbital Debris Fragments," *Earth, Moon, and Planets*, Vol. 45, 1989, pp. 29-51.

February The IG (Space) publishes *Report on Orbital Debris*, the first report on the orbital debris problem to draw on broad-based input from U.S. Federal agencies. It calls for joint NASA-DoD orbital debris studies, and mandates international cooperation on orbital debris.

Report on Orbital Debris, IG (Space), February 1989.

February The U.S. National Security Council endorses the IG (Space) report.

Ibid.

The Interagency Group (Space) Report, International Cooperation on Orbital Debris, and the Changing World of Spaceflight

According to Donald Kessler, the IG (Space) report was extremely significant, though not for its technical content. "It said what we [members of the orbital debris community] had been saying all along," he stated. The report also put on record the orbital debris views of a number of different Federal agencies. Loftus called it "the culmination of consciousness-raising activities in the U.S. government." It constituted a U.S. government consensus position on the orbital debris problem. More important in the long-term, however, the IG (Space) report was, according to Kessler, "a charter for us to educate the international community. . . if it had not been for this report, we would not have had a clear charter to do that." In effect, the U.S. government got its policy house in order, clearing the way to foster orbital debris policies and awareness beyond U.S. borders. Members of the JSC orbital debris team and NASA Headquarters officials visited Japan, the Soviet Union, Europe, and China. They shared reports on their discussions with other agencies of the U.S. government.

Only a few month after the IG (Space) report was published, revolution swept the Soviet Union's satellite states in eastern and central Europe. The border between East and West Germany was erased and the once-outlawed Solidarity movement took charge in Poland. The Cold War ended on January 1, 1992, when the tricolor flag of Russia replaced the red flag of the Soviet Union over the Moscow Kremlin. The first day of 1992, the International Space Year, saw the creation of more than a dozen new nations in eastern Europe and central Asia, as the unitary Soviet state officially ceased to exist.

Such sweeping political changes could not help but have profound implications for human space activities. Some argued that large space projects had no place in the post-Cold War world. They advocated diverting the resources of large space projects, such as SSF, SDI, Buran, the Space Exploration Initiative, and Hermes, to non-space activities. Others argued that the Cold War's end was an opportunity for increased space cooperation. Paradoxically, cooperation often benefited when spacefaring nations reduced the resources available for large space projects. Space programs strapped for cash came together where they had complementary capabilities. For example, the United States selected a modified version of the Russian Soyuz spacecraft to serve as a lifeboat for

SSF. In August 1993, Russia and the U.S. agreed to combine the SSF and Mir 2 space station programs. European and Japanese concerns about U.S. commitment to SSF gave them impetus to explore new relationships with Russia and with each other.

The common threat to human space activities from orbital debris was also a catalyst for international space cooperation. Countries exchanged knowledge and experience. They took the next step in cooperation when they began developing joint projects to study orbital debris. The United States led the way in instigating many of the cooperative orbital debris efforts, thereby helping to raise the priority assigned to orbital debris in other countries. Discussions on orbital debris became increasingly high-level and multilateral.

Report on Orbital Debris, IG (Space), February 1989; interview, David S. F. Portree with Donald J. Kessler, June 7, 1993.

March 12-18 The STS-29 Space Shuttle mission deploys a TDRS. During postflight inspection of the Space Shuttle Discovery, a hole 1 cm wide and 10 cm long is found in a Thermal Protection System tile. The hole does not resemble those commonly caused during launch and landing. Sampling reveals the presence of silver, an element not commonly used in the Shuttle orbiter, external tank, or solid rocket boosters. Confirmation that the damage was caused by orbital debris remains difficult, however, because of the techniques used to examine the hole. The impactor was probably smaller than 1 mm. No objects were detected entering the 5-km-by-25-km-by-5-km alert box during the mission, pointing up the limitations of ground-based tracking systems – at Shuttle orbital altitude the smallest object detectable is approximately 10 cm across. Only about 10 percent of the objects in orbit large enough to harm a Shuttle orbiter can be detected using conventional tracking methods.

Space Program Space Debris: A Potential Threat to Space Station and Shuttle, GAO, April 1990; J. Steven Stich, "STS Collision Avoidance Maneuvers" (presentation materials), January 17, 1992, p. 10; interview, David S. F. Portree with Michael F. Collins and J. Steven Stich, August 17, 1993.

April 4 The U.S. Congress Office of Technology Assessment (OTA) and the United States Space Foundation (USSF) sponsor the Joint Workshop on Space Debris and Its Policy Implications as part of the USSF's Fifth National Space Symposium. The workshop looks at technical, policy, and legal orbital debris issues. Joseph Loftus states that much progress has been made since 1977, when NASA became interested in orbital debris through Donald Kessler's work. "Originally," he recounts, "it was very difficult to do any consciousness raising. And it's natural to understand why. . . [s]pace is, by definition, empty. . . [s]o it's difficult to get people to understand that there can be a hazard." Loftus concludes by stating his concerns about GEO. He points out that LEO has been the focus of most orbital debris research. However, GEO growth rates are higher and objects in GEO remain aloft longer than objects in LEO. Among other speakers is Howard Baker, an environmental law and space activities specialist, who states that "on Earth, humanity's failure to account for environmental protection in planning the development of living and working communities has yielded both life-taking and life-threatening situations. [P]roblems analogous to these can be avoided in the relatively pristine environment of space."

Space: A New Era, proceedings of the Fifth National Space Symposium, Allison Kinsley, chief editor, 1989.

1989

May

Joseph Loftus, Andrew Potter, William Djinis, NASA Headquarters Orbital Debris Program Manager, and Daniel Jacobs, NASA Headquarters International Relations Office, travel to Japan to discuss orbital debris with Japanese space officials. Several preliminary agreements on future joint activities are concluded.

NASA/NASDA Technical Interchange Meeting Minutes, January 15, 1991.

May 4-8

On STS-30 the Space Shuttle Atlantis carries the first new American planetary probe in 11 years, the Magellan Venus radar mapper. Magellan and its IUS are deployed into LEO and successfully launched onto an interplanetary trajectory for a 16-month voyage to cloudy Venus. During the 4-day, 58-min Shuttle mission three objects intrude on the 5-km-by-25-km-by-5-km alert box, but none enter the 2-km-by-5-km-by-2-km maneuver box.

J. Steven Stich, “STS Collision Avoidance Procedures” (presentation materials), January 17, 1992, p. 10.

June

Karl Henize conducts the third of six 2-week orbital debris photometry sessions at Rattlesnake Mountain Observatory in Washington State. He uses the new JSC CCD Debris Telescope (CDT) to gather more data on the optical characteristics of orbital debris.

Interview, David S. F. Portree with Karl Henize, June 8, 1993.

September 25

The OTA holds a workshop on orbital debris in Washington, D.C. In attendance are representatives from NASA Headquarters, JSC, Teledyne Brown, the U.S. Army, Stanford University, the DOT, the Department of State, General Dynamics, and other organizations. The workshop is the primary information source for the OTA background paper *Orbiting Debris: A Space Environmental Problem*, published in September 1990.

Orbiting Debris: A Space Environmental Problem, OTA, 1990.

September 29

NASA agrees to use USSPACECOM’s existing Haystack radar and the planned Haystack Auxiliary (HAX) radar for orbital debris measurements. The agreement leads to cancellation of DECR. NASA accepts a USSPACECOM proposal of August 15 (as modified and expanded September 1) because data from Haystack-HAX can be available sooner than DECR data. This will permit it to support the planned 1991 SSF CDR. In addition, Haystack-HAX would be less expensive than DECR.

Space Program Space Debris: A Potential Threat to Space Station and Shuttle, GAO, April 1990; interview, David S. F. Portree with John Stanley, June 21, 1993; letter, William Lenior, NASA Headquarters, to Vice Admiral Hernandez, USSPACECOM, June 7, 1990, with enclosed Memorandum of Agreement between USSPACECOM and NASA for Orbital Debris Data Collection.

October 2

NASA and TUBS orbital debris researchers hold the first in a series of semi-annual meetings on orbital debris environment modeling in Braunschweig.

October 18-23

Atlantis deploys the Galileo Jupiter orbiter and atmospheric probe atop an IUS. During the Shuttle’s nearly 5-day mission, one space object intrudes on its 5-km-by-25-km-by-5-km alert box.

J. Steven Stich, “STS Collision Avoidance Procedures” (presentation materials), January 17, 1992, p. 10.

November 13-14 The West German government sponsors a meeting called Safety Aspects of Nuclear Reactors in Space, in Cologne. Dietrich Rex predicts that Soviet space nuclear reactors will undergo 2-3 on-orbit collisions in the next 300 years. Each will result in world-wide reentry of radioactive debris.

Note, Andrew E. Potter to David S. F. Portree, August 2, 1993.

November 22-27 STS-33 is a DoD mission. After the third night launch in Shuttle program history, Discovery enters a 28.45-deg inclination orbit for 5 days. During that time one object intrudes on its 5-km-by-25-km-by-5-km alert box. This is the last time an object enters the alert box until STS-48 in September 1991.

J. Steven Stich, “STS Collision Avoidance” (presentation materials), January 17, 1992, p. 10.

December 13-15 Donald Kessler, Joseph Loftus, Andrew Potter, William Djinis, and Daniel Jacobs meet their counterparts at TsNIIMash, the Central Research Institute for the Ministry of General Machine Building, in Moscow. In addition to TsNIIMash, NPO Energia, the Ministry of Defense, the Foreign Ministry, and GLAVCOSMOS send representatives. The Soviets take the NASA delegation on a tour of Star City, where they examine a mockup of the Mir space station. They also learn of Soviet cosmonauts’ concerns about orbital debris impacts on Soviet space stations (damage to exterior lights is mentioned). The Soviets share data from spacecraft recovered after up to a year in LEO. They reveal that their space station meteoroid shields are of Whipple design, with bumpers 0.5 to 1 mm thick suspended 70 to 100 mm above their pressure hulls. The Soviets say they plan to mitigate the debris hazard by safely deorbiting all large spacecraft, expelling oxidizer from upper stages left in orbit, and minimizing launch debris and multiple payload launches. The U.S.-Soviet Orbital Debris Working Group is established.

Thornton L. Page, Andrew E. Potter, and Donald J. Kessler, “The History of Orbital Debris,” 1990 (unpublished draft paper); interview, David S. F. Portree with Donald J. Kessler, June 7, 1993; Trip Report, Loftus Orbital Debris Files; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993.

1990

End of year launches reaching Earth orbit or beyond (since 1957)	3312
End of year satellites (objects in orbit)	6830

January 9-20 On STS-32, Columbia recovers the LDEF from a nearly circular 331-km orbit. The satellite was originally intended to spend only about a year in orbit, but its 57 experiments were forced to remain in space for nearly 6 years after the Challenger accident.

January 22 The GAO sends NASA a draft copy of its report, *Space Program Space Debris: Potential Threat to Space Station and Shuttle.*

February 13 NASA responds to the GAO report. NASA Assistant Deputy Administrator John E. O’Brien points out “misunderstandings” which he says lead the GAO to suggest NASA has been "derelict in its responsibility to protect mission crews and valuable hardware from unnecessary risks arising as a result of space debris." He states that the 1988 update of the orbital debris environment is not used in SSF design because it contains "the same large degree of uncertainty" as the 1984 model. He reports that NASA is collecting more data, citing the NASA-USSPACECOM Haystack-HAX radar agreement. O'Brien states that the impact rates and probabilities used in the GAO report are derived from the 1989 IG (Space) report, which, he says, is now out of date, as national governments and international organizations have modified their space operations to reduce the amount of orbital debris they create. He points out that the probability of debris striking SSF has become smaller, because the current SSF design measures only 2000 m^2. The design measured 5000 m^2 when the IG (Space) made its calculations. O'Brien's response is printed as an appendix in the final version of the GAO report.

> *Space Program Space Debris: A Potential Threat to Space Station and Shuttle,* GAO, April 1990, Appendix I, pp. 30-34.

March The Soviet Union pledges to inform the U.N. before it launches any more nuclear reactors into Earth orbit.

March 14 The third Intelsat 6 series satellite is launched atop a U.S. Titan 3. The cylindrical Intelsat 6 satellites are 3.63 m in diameter and 11.84 m high. They are capable of carrying 45,000 two-way telephone conversations. A separation system failure strands the satellite in LEO. It is placed in a 555-km storage orbit. The satellite is initially declared a $265-million total loss. NASA and the Intelsat organization commence planning a Space Shuttle mission to recover the satellite. It was originally meant to be launched on the Space Shuttle, so Shuttle-compatible handling equipment already exists. In addition, the enormous cost of the satellite makes practical a rescue attempt.

March 19-22 The Southwest Research Institute (SRI) in San Antonio, Texas, first presents The Growing Challenge: A Short Course on Dealing with Orbital Debris. The instructors for the course are Donald Kessler, Burton Cour-Palais, Charles E. Anderson, Jr., and Randy Tullos. Anderson is an SRI expert in the hypervelocity impact field, and Tullos is an expert on hypervelocity modeling. The course comprises 30 percent environment modeling, 30 percent hypervelocity penetration mechanics, 20 percent design and validation considerations, and 20 percent shielding design.

> Brochure, "The Growing Challenge: A Short Course on Dealing with Orbital Debris," Southwest Research Institute.

April The GAO publishes *Space Program Space Debris: a Potential Threat to Space Station and Shuttle*.

April TUBS and JSC representatives hold a meeting on orbital debris modeling in Houston.

April 16-19 AIAA sponsors the AIAA / NASA / DoD Orbital Debris Conference in Baltimore. Researchers from Europe and Japan participate, reflecting growing international concern over orbital debris. This is the first major orbital debris conference since 1982. Paper topics include orbital debris shielding for the U.S., European, and Japanese SSF modules, modeling the debris environment, debris detection using optical telescopes, radars, and IRAS, and analysis of returned spacecraft surfaces.

> *Orbital Debris: Technical Issues and Future Directions* (NASA CP 10077), Andrew E. Potter, editor, September 1992, p. i.

June 7

William Lenoir, NASA Associate Administrator for Space Flight, sends a letter to Vice Admiral D. E. Hernandez, Deputy Commander in Chief of USSPACECOM. He encloses a signed memorandum of agreement (MOA) on Haystack-HAX. He opens his letter by declaring that the "timely collection of orbital debris data to support the Space Station Freedom is of very high priority." The MOA lists U.S. Air Force Space Command as USSPACECOM's representative in the arrangement, and JSC as NASA's. The agreement stipulates that NASA will pay $11.38 million for the HAX radar and for modifications to Haystack. In exchange for paying for part of the maintenance and operations of the Haystack radar, NASA will receive at least 400 hours of Haystack data in fiscal year (FY) 1990 and 800 in FY 1991. In FY 1992 NASA will receive 700 hours each from the Haystack and HAX radars. From FY 1993 through FY 1997, NASA will receive 800 hours from each radar. If NASA elects to use the planned Ground Based Radar-Experimental (GBR-X) facility on Kwajalein Atoll, USSPACECOM will provide 700-1200 hours of data per year for 5 years beginning when GBR-X is operational. If NASA elects not to use the GBR-X, it will build an equatorial site radar, and USSPACECOM will pay for operations and maintenance. Vice Admiral Hernandez signs the MOA on June 12.

> Letter, William Lenior, NASA Headquarters, to Vice Admiral Hernandez, USSPACECOM, June 7, 1990, with enclosed Memorandum of Agreement between the USSPACECOM and NASA for Orbital Debris Data Collection.

June 25-July 6

At the COSPAR XXVIII meeting in the Hague, Netherlands, Donald Kessler presents "Collisional Cascading: The Limits of Population Growth in Low Earth Orbit." According to Kessler, collisional cascading will occur

> . . . in the long term. . . [when] a critical population density is reached, [and] the rate of fragment production from random collisions exceeds the rate of removal by atmospheric drag. Once this critical density is reached, the debris population will increase without placing any more objects into orbit. This increase will stop only when the population of large objects is sufficiently reduced, either by active removal or by fragmentation. However, by the time fragmentation reduces the population of large objects, the resulting debris environment is likely to be too hostile for future space use. . . . [T]he data that already exists is sufficient to show that cascading collisions will control the future debris environment with no or very minor increases in the current low Earth orbit population. Two populations control this process – explosion fragments and expended rocket bodies and payloads. Practices are already changing to limit explosions in low Earth orbit. It is now necessary to begin limiting the number of expended rocket bodies and payloads in orbit.

In his concluding remarks, he reports that some LEO regions are already unstable. Assuming no increase in the LEO population, the rate of new debris production will be slow – one breakup every 10-20 years, depending on the size of the uncatalogued population – with half the breakups in the unstable regions. Large debris objects produced will remain confined to the unstable regions. However, small debris will be ejected into other orbits, "increasing the amount of small debris in LEO for centuries."

Donald J. Kessler, "Collisional Cascading: The Limits of Population Growth in LEO," *Advanced Space Research*, Vol. 11, No. 12, 1991.

July

NASA and DoD begin the joint orbital debris studies called for in the IG (Space) report of February 1989. The U.S. Air Force is lead service, with the Air Force Space Technology Center (Phillips Laboratory) as DoD technical lead. NASA chooses JSC as its technical lead. The joint NASA / DoD research program plan is approved by the National Space Council this month. It has two objectives – to characterize the LEO debris environment down to 1 mm, and to identify candidate technologies for minimizing debris production and enhancing spacecraft survivability. Implementation of the second objective depends on the results of the environment studies called for in the first objective. NASA and the DoD also begin work on a guide for spacecraft builders and launch operators, which they plan to call the *Space Debris Minimization and Mitigation Handbook.*

Albert Reinhardt, Jr., "Potential Effects of the Space Debris Environment on Military Space Systems," presented at the Preservation of Near-Earth Space for Future Generations symposium, University of Chicago, June 24-26, 1992.

August

At North Carolina State University (NCSU) teams of students compete to design systems for deploying radar calibration spheres from a Space Shuttle in LEO. Andrew Potter and John Stanley foster the project, which develops into the Orbital Debris Radar Calibration Spheres (ODERACS) experiment.

Interview, David S. F. Portree with John Stanley, July 30, 1993.

August 11-14

In St. Petersburg, the joint U.S-Soviet Orbital Debris Working Group holds its second meeting.

Autumn

John Stanley conducts a three-part test to calibrate the Haystack Radar for orbital debris studies. In the first part he selects 100 1-5-cm pieces of a satellite fragmented on Earth in a DoD experiment. The pieces are characterized using the radar calibration laboratory at Science Planning Corporation in Virginia. Algorithms are developed for interpreting the radar signatures of the pieces. In the second part of the test, nine pieces are dropped by balloons from altitudes between 12,500-20,000 m at Kwajalein Atoll, in the Marshall Islands. The four radars of the Kiernan Reentry Measurements Site track the objects. The XonTech Corporation analyzes the radar results and correctly determines the sizes and shapes of the pieces. The radars also take data on over 100 satellites. The third part of the test involves tracking 25 objects in orbit using optical sensors and radars simultaneously, with the aim of comparing observed characteristics.

John Stanley and Eugene Stansbery, "Orbital Debris Measurements," *The JSC Research and Technology Annual Report 1990* (NASA TM 102172), pp. II 17-18; interview, David S. F. Portree with John Stanley, June 21, 1993.

September The OTA publishes *Orbiting Debris: A Space Environmental Problem*, a background paper largely based on the September 25, 1989, orbital debris workshop in Washington, D.C. Additional information was drawn from the April 4-7, 1989, Fifth National Space Symposium, jointly sponsored by the OTA and the USSF, the 1989 IG (Space) report, and the 1988 ESA report. The OTA report presents eleven commonly-held concerns of the orbital debris community. They are

- Prompt action is called for from space users, lest certain orbits be restricted in the near future.
- Better data is needed on the orbital distribution and size of debris.
- Additional debris mitigation techniques need to be developed.
- Paying for debris removal is not warranted at this time.
- Protection technologies (shielding) can reduce the debris hazard.
- The threat to the lives of astronauts and cosmonauts posed by high-speed objects in LEO is significant.
- Active involvement by all space-faring nations is required to control orbital debris.
- Existing treaties are inadequate for minimizing debris.
- Legal issues, such as the definition of the term orbital debris, jurisdiction and control over orbital debris, and liability for damage caused by orbital debris must be resolved.
- Private sector space users will need to aid governments in mitigating the orbital debris population.
- International education on orbital debris is necessary as many misconceptions exist about the problem.

Orbiting Debris: A Space Environmental Problem, OTA, 1990.

September The Japan Society for Aeronautical and Space Sciences (JSASS) founds its Space Debris Study Group. It aims to "promote overall space debris-related research, to stimulate public awareness of this issue and to provide guidelines to cope with it."

Susuma Toda, "The Current and Future Space Debris Environment as Assessed in Japan," presented at the Preservation of Near-Earth Space for Future Generations symposium, University of Chicago, June 24-26, 1992.

September NASA and NASDA hold their first Technical Interchange Meeting (TIM) on SSF meteoroid and orbital debris issues at MSFC. After the meeting, NASDA reevaluates the Japanese Experiment Module (JEM) meteoroid and orbital debris shielding development process and determines that a new process should be established.

> Memorandum to Distribution with enclosures , "NASA/NASDA TIM Minutes," from Raymond L. Nieder, Chairman, JSC Meteoroid and Debris Protection Working Group, January 15, 1991.

September At the AIAA Space Programs and Technologies Conference in Huntsville, Alabama, Eric Christiansen, Research Engineer, JSC Hypervelocity Impact Test Facility (HIT-F) (formerly the Orbital Debris Impact Laboratory), Jeanne Lee Crews, HIT-F Manager, and Jennifer Horn, Aerospace Engineer, MSFC, describe ways of augmenting SSF orbital debris shielding to prevent critical damage to the station during its planned 30-year lifetime. They use the 1988 Kessler-Anderson orbital debris environment model. They report that "the small and medium debris environment is predicted to be worse than was expected when the SSF program began," and that the problem will "grow with time, becoming even more severe during station assembly and operations." The researchers contend that the existing module design will be adequate for only 6-9.5 years after SSF deployment. They propose that the baseline shielding be augmented after SSF assembly is completed. This would permit the original design to be used. The augmentation configuration could also be tailored to meet unforeseen demands of the changing orbital debris environment. They suggest that the baseline SSF Whipple Bumper be augmented with the Multi-Shock Shield (MSS) invented by Burton Cour-Palais and Crews, or by Christiansen's Mesh Double-Bumper (MDB) shield (fig. 6). They also propose systems which would activate only when a debris impact is imminent, such as inflatable Nextel ceramic fabric MSS airbags. To reduce the population of small orbital debris, the researchers suggest deployment of a 1-10-km diameter space sweeper comprising a multilayer Nextel balloon. The sweeper would move through space independent of SSF, impacting with and absorbing debris particles. They describe methods for delivering augmentation shielding to the station and deploying it with minimal astronaut EVA time.

> Jeanne Lee Crews and Burton Cour-Palais, "A Multi-Shock Concept for Spacecraft Shielding," *International Journal of Impact Engineering*, Vol. 10, 1990, pp. 135-146; Eric Christiansen, Jennifer Horn, and Jeanne Lee Crews, "Augmentation of Orbital Debris Shielding for Space Station Freedom," AIAA paper 90-3665, AIAA Space Programs and Technologies Conference, September 25-28, 1990.

October The U.S. Air Force Haystack radar on Millstone Hill, Tyngsboro, Massachusetts, commences occasional observations of orbital debris.

October 4 The Chinese launched the Fengyun 1-2 weather satellite atop a Long March 4 rocket on September 3, 1990. On this date the rocket's upper stage explodes, producing more than 80 trackable debris pieces. It described a 895-km-by-880-km orbit at an inclination of 89.9 deg.

October 22 A Cooperation Meeting on Orbital Debris is held in Braunschweig between representatives of JSC, Deutsche Agentur für Raumfahrtangelegenheiten (DARA), and TUBS. The main topic is orbital debris environment modeling.

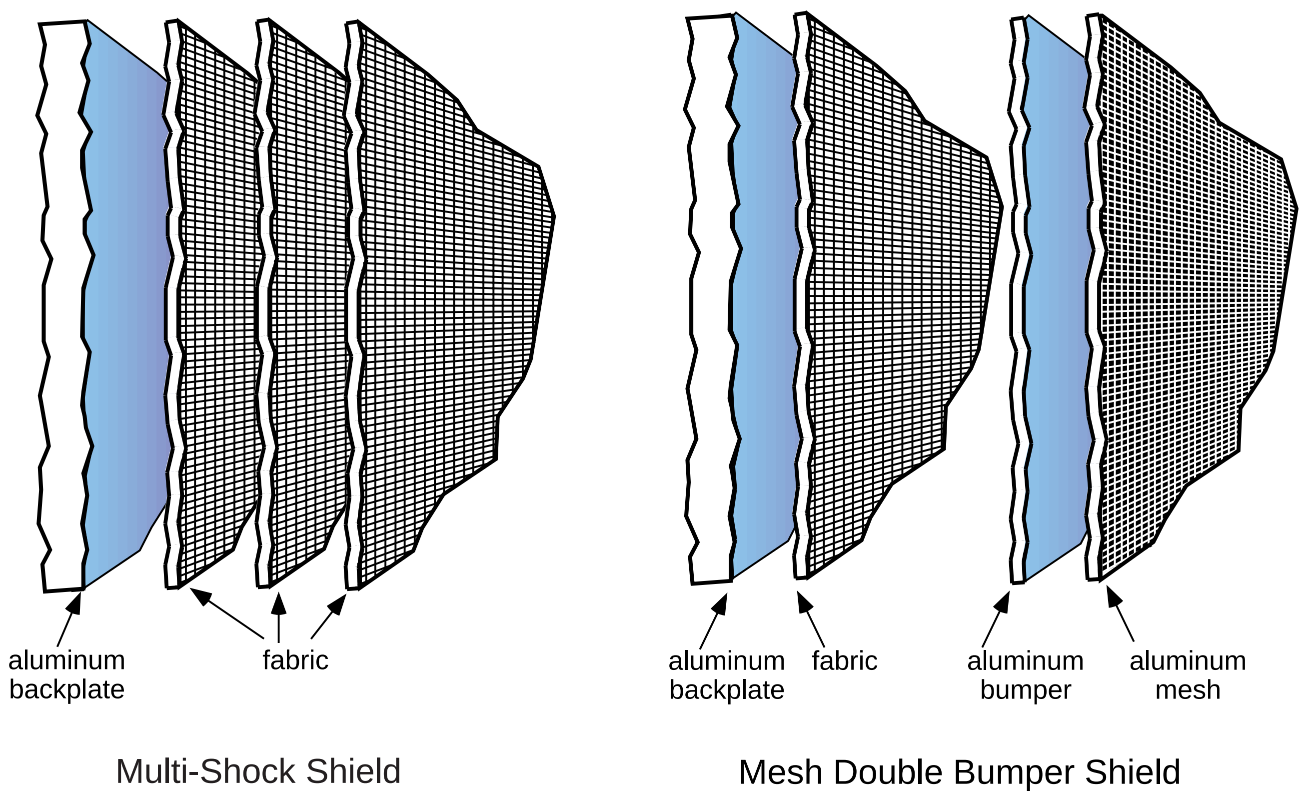

Figure 6.

The Multi-Shock Shield (MSS) and Mesh Double Bumper (MDB) are variations on the Whipple Bumper (see fig. 4) designed to reduce its weight and enhance its effectiveness as protection against orbital debris. The MSS (top) relies on multiple layers of ceramic fiber to disrupt impactors and shock them to higher temperatures. They melt and sometimes vaporize before they reach the aluminum backplate (the spacecraft hull). The MDB (bottom) augments the basic Whipple design by placing a layer of lightweight ceramic fabric between its aluminum bumper and the aluminum backplate (again, the spacecraft hull). A layer of lightweight aluminum mesh is placed above the bumper. The mesh disrupts impactors, permitting the bumper to be thin and light. The layer of ceramic fabric catches fragments of the impactor which penetrate the bumper as well as fragments of the bumper punched out by the impactor (these can under certain conditions cause more damage to the spacecraft hull than the original impactor). See also the Stuffed Whipple (fig. 8).

October 24-25 NASA and ESA hold their Fifth Space Debris Coordination Meeting at the ESA European Space Operations Center (ESOC) in Darmstadt, Germany. Helmut Heusmann of the ESA-ESOC Columbus System Division describes meteoroid and orbital debris protection systems on the ESA Columbus SSF module. Donald Kessler describes the 1988 orbital debris environment model (modified 1990), the basis for proposed revisions to the SSF orbital debris design requirements.

Draft of Minutes of the Fifth ESA-NASA Space Debris Coordination Meeting, October 24-25, 1990.

November 13 Four years after the Ariane V16 upper stage explosion, ESA estimates that the orbits of the pieces produced have spread to form a shell around the Earth. Only the extreme northern and southern latitudes of the Earth are not overflown by Ariane V16 debris.

November 13 The Subcommittee on Micrometeor and Debris Protection of the Space Station Advisory Committee, led by Edward Crawley of MIT, publishes its findings and recommendations on this date. The report is based largely on two fact-finding sessions held in June 1990 at the Space Station Program Office in Reston, Virginia, and at JSC. It recommends that NASA adopt the 1988 Kessler-Anderson orbital debris model, as modified by memorandum SN3-90-68 (1990). The Subcommittee states that “this model is currently the best available and is supported by data from Solar Max and various ground observatories.” They also recommend a review of the orbital debris environment every 5 years, a permanent board to assure SSF survivability, and a memorandum of understanding arranging for USSPACECOM to provide services and information on the orbital environment during the SSF operations phase. The Subcommittee calls for exchange of data on orbital debris and micrometeoroids with other nations. They single out the Soviet Union, which they say has “extensive long-duration orbital experience.”

“Report of the Subcommittee on Micrometeor and Debris Protection,” Space Station Advisory Council, November 13, 1990.

1991

End of year launches reaching Earth orbit or beyond (since 1957)	3400
End of year satellites (objects in orbit)	7049

January 15-17 NASA and NASDA hold a TIM at JSC on SSF orbital debris issues. NASDA seeks to coordinate with NASA the resolution of problems encountered in implementing the new JEM orbital debris shielding development process. The basic JEM shielding comprises a pressure wall/backplate 3.2 mm thick and two aluminum bumpers. The bumpers have a total thickness of less than 4 mm. The outer bumper is 102 mm from the backplate. Multilayer insulation is attached to the inner surface of the inner bumper.

Memorandum to Distribution with enclosures, “NASA/NASDA Technical Interchange Meeting Minutes,” from Raymond L. Nieder, Chairman, JSC Meteoroid and Debris Protection Working Group, January 15, 1991.

February 5 The Congressional Research Service (CRS) of the Library of Congress releases a report on orbital debris by Marcia S. Smith, Aerospace Policy Specialist in the Science Policy Research Division. The document, which is titled *Space Debris: A Growing Problem*, is prepared for Members and committees of Congress. It runs six pages, and references White House, GAO, OTA, and ESA reports on orbital debris published since 1988. Smith's report references no NASA sources, but the sources it uses depend almost entirely on NASA reports and experts for their information.

Marcia Smith, *Space Debris: A Growing Problem*, Congressional Research Service, Library of Congress, 1991.

February 7 After hosting more than 20 cosmonauts, Salyut 7 was finally abandoned in mid-1986 with the large Cosmos 1686 module still attached. The 43-ton combination was boosted to a higher altitude to forestall reentry, and plans were floated to revisit the derelict station in the future to collect materials exposed to spaceflight conditions for year. It was even suggested that the Soviet space shuttle Buran could return the entire core station to Earth. In late 1989 cosmonaut Vladimir Dzhanibekov, a former Salyut 7 resident who helped rescue the station in 1985, called plans to retrieve Salyut 7 "fantasy." Controlled deorbit was not an option, he said, because the station contained no fuel. Plans to deorbit Salyut 7 using the engines on an automated Progress freighter or manned Soyuz were complicated by the station's slow, wobbling spin. On this date the Salyut 7 / Cosmos 1686 combination makes an uncontrolled reentry over Argentina. The Soviets announce in advance that at least 1500-2000 kg of the complex are expected to reach the ground, including the large reentry module attached to Cosmos 1686. Traffic controllers at Buenos Aires International Airport watch the fireball for 2 minutes. Large pieces are found northwest of the Argentine capital. A piece the size of a car lands 500 km north of Buenos Aires and sets fire to trees. No other injuries or property damage are reported.

"News Breaks," *Aviation Week & Space Technology*, February 11, 1991, p. 15; "Soviets plan to 'scuttle' Salyut 7," *Spaceflight*, The British Interplanetary Society, January 1990, p. 7; Loftus Orbital Debris Files.

April NASA and TUBS hold a meeting on orbital debris modeling at JSC.

April 9 The International Workshop on the Salyut 7 / Cosmos 1686 Reentry is held at ESOC.

Salyut 7/Cosmos 1686 Reentry (ESA SP-345), B. Battrick, editor, ESA-ESOC, August 1991.

April 16-17 NASA and ESA hold their Sixth Orbital Debris Coordination Meeting at JSC. Participants discuss ESA and NASA LDEF research and other topics.

Minutes of the Sixth ESA/NASA Space Debris Coordination Meeting, April 16-17, 1992.

May 1 Nimbus 6, a weather satellite, was launched on a Delta rocket on June 12, 1975. On this date its derelict Delta second stage explodes in orbit, producing 237 trackable debris pieces. About 190 remained in orbit on January 1, 1998.

May 15 Joseph Loftus and Eugene Stansbery meet CNES and Arianespace officials in Evry, near Paris. They discuss provisions for debris control for the planned

Ariane 5 booster. Loftus is in Paris to attend the Fourth European Aerospace Conference, where he chairs a session on orbital debris.

Joseph P. Loftus, Jr., "Trip Report – Discussion with CNES-Arianespace and ESA, re: Ariane 5."

June The Haystack radar begins providing calibrated useful data to orbital debris researchers at JSC. MIT-LL, which operates Haystack on contract to the U.S. Air Force, collects data on magnetic tape and sends it to JSC. JSC's Orbital Debris Data Analysis Facility then transfers the data to optical disks and analyzes it. Each January JSC provides the SSF program with an orbital debris environment report based on the Haystack measurements.

Interview, David S. F. Portree with John Stanley, June 21, 1993.

June During the annual 2-week optical debris detection session at Rattlesnake Mountain Observatory in Washington State, Karl Henize uses the JSC CDT to make 655 observations of 270 objects.

Interview, David S. F. Portree with Karl Henize, June 8, 1993.

June John Stanley briefs a Haystack Radar peer review group on the NCSU contest to develop a radar calibration sphere deployment system. The peer review group calls for orbital debris radar calibration spheres to be deployed in orbit as soon as possible.

Interview, David S. F. Portree with John Stanley, July 30, 1993.

June 2-8 NASA holds the First LDEF Post-Retrieval Symposium in Kissimmee, Florida. *The LDEF Space Environmental Effects Newsletter* reports that "the major achievement to date in the analysis of LDEF meteoroid and debris data is a preliminary comparison of the combined environment and its effects observed on LDEF with existing models." Less than 10 percent of the significant impact pits on LDEF have been analyzed by this date. However, impact pits on LDEF's trailing surfaces provide the first clear evidence for debris in elliptical orbits. Researchers also find impact pits formed by small particles accelerated from the direction of the Sun by solar radiation, and evidence for debris clouds produced by the Shuttle and other launch vehicles.

"Summary of the First LDEF Post-Retrieval Symposium," *LDEF Space Environmental Effects Newsletter*, Vol. 2, No. 3, June 15, 1991; *LDEF – 69 Months in Space: First Post-Retrieval Symposium* (NASA CP 3134, Part 1), Arlene Levine, editor, 1991.

June 6 USSPACECOM issues "Minimization and Mitigation of Orbital Debris" (USSPACECOM Regulation 57-2). It lists guidelines for the operation and development of current and future space systems, with an eye toward mitigating the production of orbital debris. In 1992 an AIAA special report states that some of its provisions could "serve as models for the civil sector agencies" in the development of orbital debris policies.

Orbital Debris Mitigation Techniques: Technical, Economic, and Legal Aspects, AIAA Special Project Report SP-016-1992.

June 11 New SSF orbital debris shielding design requirements based on the 1988 Kessler-Anderson orbital debris environment model, as amended by a 1990 memorandum, are submitted to the Space Station Control Board for consideration.

June 11-12 Joseph Loftus, Andrew Potter, Donald Kessler, Daniel Jacobs, and George Levin, NASA Orbital Debris Program Manager, travel to Japan for orbital debris discussions. They visit NASDA Headquarters, the light-gas guns at Mitsubishi Heavy Industries, and other facilities.

Trip report memorandum, Loftus Orbital Debris Files.

June 12 The International Radio Consultative Committee (CCIR) of the International Telecommunications Union (ITU) formulates a draft recommendation stating that "as little debris as possible should be released into geostationary orbit" and that "every reasonable effort should be made to shorten the lifetime of debris in transfer orbit." The non-binding recommendation also states that GEO satellites should be transferred to "supersynchronous graveyards" (orbits above GEO altitude) at the end of their useful life. No minimum acceptable graveyard altitude is recommended.

Pamela Meredith, "A Legal Regime for Orbital Debris: Elements of a Multilateral Treaty," presented at the Preservation of Near-Earth Space for Future Generations symposium, University of Chicago, June 24-26, 1992.

GEO and Orbital Debris

GEO contains far fewer objects than LEO. The GEO population was 545 known spacecraft on January 1, 1998. This number does not include spent upper stages. The number of spacecraft placed in GEO is about 30-35 objects / year, and an increasing number of satellites are boosted out of GEO at end of mission. If the current GEO population did not change, we would not see our first significant debris-producing collision for about 10,000 years. If the present rate of population increase continues, however, our first collision will likely occur in less than a century. If the increase rate grows, then the first collision will, of course, occur sooner.

Atmospheric drag plays little role in the decay of GEO debris. Solar radiation pressure can remove micron-size debris particles (those with the least potential for causing damage) in less than a year. Intermediate-size particles (a fraction of a 1 mm to 1 cm) are made to decay by a combination of solar radiation pressure and the solar radiation pressure drag component (the Poynting-Robertson Effect). Even so, they need at least 60,000 years to leave GEO. Large objects, like intact satellites, require a million years or longer to leave GEO.

Uncontrolled objects in GEO drift in longitude. Their orbital plane also precesses with a period of 53 years. As a result, about 20 years after active station-keeping ends, a satellite's orbit reaches an inclination of about 15 deg. The inclination of the orbit cycles back to 0 deg 53 years after station-keeping ends. The cycle then repeats.

Satellites in 15-deg inclination orbit cross the equatorial belt twice each day. The difference in velocity between a satellite in a 15-deg inclination GEO orbit and one at equatorial inclination is about 800 m / second. This is faster than a jet aircraft.

Several GEO users have instituted a policy of clearing GEO by changing the orbital height of their satellites when they near the end of their planned useful lives. The JSC orbital debris team and ESA have jointly agreed that minimum separation distances above or below GEO in the hundreds of kilometers should be used. Objects should be moved to at least 300 km from GEO, plus 2000 km for every m^2/kg of satellite to compensate for the effects of solar radiation pressure. For example, for a 10 m^2 satellite weighing 1000 kg, 20 km of altitude would need to be added to take into account solar radiation pressure. This yields a recommended graveyard orbit altitude of 320 km.

Another opportunity for GEO debris management is the stable plane. The stable plane is inclined 7.3 deg to the Earth's equator, and has a right ascension (RA) of 0 deg (that is, the plane is inclined toward the Sun). Satellites do not achieve the stable plane RA without intervention by their operators. Once a satellite is in the stable plane, no station-keeping is needed to maintain that orbital plane. The collision velocity between satellites in the stable plane is 5 m / second – about as fast as a running person. This is useful for orbital debris management because low-velocity collisions produce far fewer pieces than high-velocity collisions.

Stable plane orbits above or below GEO altitude use the best features of the stable plane and graveyard orbit strategies. However, neither the stable plane nor graveyard orbits hundreds of kilometers above GEO can do anything to protect GEO from satellite explosions. These can be prevented only by depleting stored energy sources. If stored energy source depletion is not routinely employed, graveyard orbits thousands of kilometers above GEO will be needed to protect it for future human use.

Joseph P. Loftus, Jr., "Orbital Debris Issues in GEO" (presentation materials), June 1992; interview, David S. F. Portree with Donald J. Kessler, June 23, 1993; Larry Jay Friesen, "Orbital Debris and Power Satellites," *The Journal of Space Development*, May, June 1993.

June 12-22 Joseph Loftus, Andrew Potter, Donald Kessler, George Levin, NASA Headquarters Office of Space Flight, and Daniel Jacobs visit the People's Republic of China. They hold orbital debris discussions with the Chinese Academy of Space Technology and other organizations. The Chinese report they formed their Orbital Debris Study Group in 1989. It has representatives from the Ministry of Aerospace Industry, the Chinese Academy of Science, the Science Commission, and the Foreign Ministry. A major topic of the meeting is the breakup of the Fengyun 1-2 satellite's Long March 4 launch vehicle upper stage on October 4, 1990. NASA describes modifications made to U.S. Delta, Japanese H-1, and European Ariane rockets to avoid explosions. The sides discuss making similar modifications to the Long March 4 upper stage.

Trip Report, Loftus Orbital Debris Files; note, Andrew E. Potter to David S. F. Portree, July 24, 1993.

July The new SSF shielding requirements based on the 1988 Kessler-Anderson orbital debris environment model, as modified by a 1990 memorandum, are accepted by the Space Station Control Board.

July 17 ESA's first ERS (European Remote Sensing) satellite is launched atop an Ariane 4 rocket into a 782-km-by-777-km, 98.5-deg sun-synchronous orbit. ERS-1 carries ground-pointing radar altimeter, radiometer, and microwave sensors. The satellite, which cost $550 million, provides data to subscribing receiving stations on every continent save Africa. Mass at the beginning of operations is 2384 kg. ERS-1 measures 11.8 m high and 11.7 m across its solar arrays. The size, orbital altitude, and importance of the ERS-1 satellite make it especially vulnerable to orbital debris. It is only one of an increasing number of large, extremely costly satellites. The loss of any one of these to orbital debris would seriously damage the space programs of which they are part.

August 5-8 In St. Petersburg, representatives from NASA meet Soviet representatives from the Institute for Space Research (IKI), the Foreign Ministry, and the KOSMOS organization. They discuss exchange of satellite catalogs and flown witness plates, flight of a NASA capture cell experiment on Mir, timely exchange of data on major breakups, and means of cataloguing debris events.

Trip report, Loftus Orbital Debris Files.

September JSC engineers select a multi-spring design from among the working prototypes of a debris calibration sphere deployment system designed and built by NCSU students. JSC begins ODERACS flight hardware fabrication. John Stanley is flight hardware program manager and experiment Principal Investigator. Development proceeds toward a planned September 1992 launch.

Interview, David S. F. Portree with John Stanley, July 30, 1993.

September 12-18 On the STS-48 mission, Space Shuttle Discovery deploys the Upper Atmosphere Research Satellite (UARS), an important component of NASA's Mission to Planet Earth program. The STS-48 mission lasts 5 days, 8 hours. Twice space objects enter Discovery's 5 km-by-25-km-by-5-km alert box. One, the spent Cosmos 955 upper stage (launched in 1977), intrudes on the 2-km-by-5-km-by-2-km maneuver box. Discovery avoids it by firing its thrusters for 7 seconds, slowing its motion by about 0.6 m / second. This is the first time an orbital debris avoidance maneuver is conducted in the history of spaceflight.

"STS-48 Mission Report," NASA JSC, October 1991; J. Steven Stich, "STS Collision Avoidance" (presentation materials), January 17, 1992, p. 10.

November In a paper published this month, Phillip Anz-Meador and Andrew Potter write that they have applied the NASA EVOLVE evolutionary debris environment computer model to determine the collision risk for Soviet space nuclear reactors. Their study confirms that several collisional breakups among the more than 30 reactors in orbit can be expected in the next few centuries.

Phillip Anz-Meador and Andrew E. Potter, "Radioactive Satellites: Intact Reentry and Breakup by Debris Impact," *Advanced Space Research*, Vol. 11, 1991, pp. 37-42.

November JSC and USSPACECOM sign an MOA on Space Station orbital debris collision avoidance support.

November 1 Leonid A. Gorshkov, Head of the Department of Orbital Station Design, Energia Design Bureau, talks with members of the JSC orbital debris team while in Houston to speak at the Exploration 91 meeting. He was the Chief Designer of the Mir space station. Gorshkov and other Energia officials discuss participation by the design bureau in U.S.-Soviet Orbital Debris Working Group discussions scheduled to take place in Moscow. They also discuss flying a U.S. capture cell on Mir and Soviet experience with orbital debris gained during the Mir program. The Soviet delegation shows little interest in sharing returned capture cells, but does express interest in exchange of services – specifically in NASA help to set up a communications relay for Mir for the period of its orbit when it is out of sight of Soviet ground stations and communications ships. They tell the JSC team they want NASA to buy space on Mir for the capture cell. The Soviet delegation also describes the Mir pressure hull. It is a chemically milled sheet 2 mm thick with webs 4 mm thick welded to form the station's cylindrical body. The largest cylinder (the main compartment) is covered by a body-mounted radiator with a 20-mm standoff from the pressure hull. The radiator is 2 mm thick. The smaller cylinders are covered by a multilayer thermal blanket comprising 40 layers of aluminized Mylar and scrim. Several layers of Kevlar-like material cover the thermal blanket. Gorshkov reports that Mir has suffered impact damage on its outer windows and on the flat sealing surface of one of its six docking rings. The Soviet officials do not wish to discuss the exact nature of the damage because doing so would compromise a commercial proposal they plan to make to Boeing Corporation of Seattle, Washington.

"Memorandum for the Record," Joseph P. Loftus, Jr. to Andrew E. Potter, November 4, 1991.

November 16

JSASS and ISAS hold the Space Debris Workshop 91 in Sagamihara, Japan. International orbital debris experts participate in the workshop, which constitutes an important step forward for Japan's development of an orbital debris policy.

November 24-December 1

The manifest for the STS-44 mission includes several DoD experiments. Atlantis maneuvers to avoid a spent Soviet upper stage which intrudes deep into its 5-km-by-25-km-by-5 km alert box. It passes very near the edge of the orbiter's 2-km-by-5-km-by-2-km maneuver box. The MCC elects to conduct an avoidance maneuver 10 hours ahead of the predicted conjunction at a time "consistent with payload objectives and crew timeline." The crew fires two +X (aft) thrusters for 7 seconds.

"STS-44 Mission Report," NASA JSC, January 1992; J. Steven Stich, "STS Collision Avoidance Procedures" (presentation materials), January 17, 1992, p. 10.

December

In March 1988, Faith Vilas received funding for a Phase A study of the Debris Collision Warning Sensors flight experiment. The experiment would be carried in the Space Shuttle payload bay, and would sample the debris population in LEO and GEO. It would use infrared and visible light sensors to study debris down to 1 mm dia in LEO and objects as small as 3 cm to an altitude of 2000 km. Vilas presented results of the Phase A study to the NASA Headquarters Office of Aeronautical and Space Technology in August 1988. The experiment was augmented to include a plan to release objects, the properties of which would be characterized on the ground before launch, from the Shuttle payload bay. These would be observed by the Debris Collision Warning Sensors. JSC carries out in-house Phase B studies. In April 1989, Kaman Sciences and Ball Electro-Optics / Cryogenics Division were selected to carry out additional Phase B studies, which were completed in April 1991. Faith Vilas was Principal Investigator, and C. Donald Harris of JSC was Project Manager for the contracted Phase B studies. In July 1991 Harris and Vilas presented Phase B results to Arnold D. Aldrich, Associate Administrator of the NASA Headquarters Office of Aeronautics, Exploration, and Technology. Aldrich asked them to study ways of reducing costs. He also suggested the use of existing sensors, and placement of the experiment on a free flying platform and SSF. This month Ball and Kaman Sciences present final extended Phase B study results at JSC. Cost is estimated at $50 million. The Shuttle-borne option is found to be less expensive than the SSF or free-flyer options. A Shuttle payload proof-of-concept experiment using visible light only is priced at $8.9 million. NASA elects not to fund the experiment through the development Phase C / D because of costs.

Note, Faith Vilas to David S. F. Portree, December 3, 1993.

1992

End of year launches reaching Earth orbit or beyond (since 1957)	3495
End of year satellites (objects in orbit)	7320

During the year An informal team of orbital debris researchers, with cooperation and support from the DoD service space commands, the Naval Research Laboratory, Raytheon, XonTech, Lockheed, Mitre, and other organizations, conducts a year-long feasibility study of the "design of a family of instruments and the configuration of a network to provide collision avoidance for the space station and all other high value assets in low earth orbit against a threat environment of 1-cm particles." It would comprise a fence of dedicated debris sensors extending thousands of km across the Earth's surface. The system would shrink the 2-km-by-5-km-by-2-km Shuttle maneuver box to about 100 m on a side (space station size), reducing the number of SSF debris avoidance maneuvers required. As many as 20 avoidance maneuvers per year would be required if the station were to use the Shuttle maneuver box, playing havoc with sensitive experiments dependent on extended periods of microgravity. The team finds that "to move the threshold of the [existing] Space Surveillance Network [SSN] from 10-30 cm to 1 cm, one needs to upgrade the sensors from 70-cm. . . to 5-cm wavelengths. To accommodate that change in sensitivity and the increase in targets that will be detected one needs to improve the database processing." The team points to experience gained using the SSN, GBR-X, and other systems to support its assertions. The total cost of setting up the system is given as $1 billion, with an annual operating cost of $100 million. The team states that this estimate "may sound high but such a system could 'shut down' numerous less capable facilities [so] the savings might pay for the new capability in a very few years." The ground-based system could be augmented with onboard optical sensors of the type studied by Ball Aerospace and Kaman Sciences under direction of Vilas and Harris. They would further reduce the false alarm rate by providing additional location data on objects tagged as collision threats by the ground-based system. The informal team briefs Space Station Program management on December 4, 1992.

Note, Joseph P. Loftus, Jr., to David S. F. Portree, September 9, 1993; interview, David S. F. Portree with Joseph P. Loftus, Jr., August 25, 1993; interview, David S. F. Portree with Joseph Loftus, December 3, 1993.

January The Space Debris Study Group of JSASS publishes its Interim Report. The report was summarized by Susuma Toda of the National Aerospace Laboratory of Japan at the University of Chicago Centennial Symposium, June 24-26,

1992. According to Toda, the report presents an overview of orbital debris issues, with particular attention paid to Japanese contributions in the field. The report cites observations made by Kyoto University's Middle and Upper atmosphere radar (MU) and optical observations of GEO objects by the Communications Research Laboratory (CRL) 1.5-m telescope as sources of orbital debris data. Only known GEO satellites were detected. Toda states that the report declares Japan's debris record to be "clean," though debris-producing "past mission failures concerned with the upper stage motor collision [the ECS-1 satellite collided with its own upper stage in 1979] and abnormal engine burning" are acknowledged. Toda states that the report characterizes NASDA's orbital debris achievements as "still very limited compared with those of the U.S.A. and Europe."

Susuma Toda, "The Current and Future Space Debris Environment as Assessed in Japan," Presented at the Preservation of Near-Earth Space for Future Generations symposium, University of Chicago, June 24-26, 1992.

January 10

Oscar 22, an unused satellite of the Transit series, is destroyed by a 150-gm aluminum pellet traveling at 6 km / second at the U.S. Air Force AEDC. The purpose of the exercise is to simulate an orbital debris strike on a satellite in orbit. Many more micron-sized particles are created than expected.

Interavia Space Directory 1992-93, Andrew Wilson, editor, p. 183.

February 9-10

An orbital debris modeling coordination meeting is held at TUBS in Germany. Papers are presented on solid rocket motor particulates, optical and radar orbital debris measurements, the Tethered Remover Satellite (TERESA) concept, and other issues. Representatives from JSC, TUBS, and DARA participate.

Minutes of Orbital Debris Modeling Coordination Meeting, NASA and TUBS, February 9-10, 1992.

February 10

By this date, 1092 hours of orbital debris data have been collected as a result of the Haystack-HAX agreement between USSPACECOM, MIT-LL, and NASA.

Minutes of the Seventh Space Debris Coordination Meeting, ESA/U.S./Japan, February 12-13, 1992.

February 12-13

The Seventh Space Debris Coordination Meeting is held at the European Space Technology Center (ESTEC) in Noordwijk, the Netherlands. Japan, NASA, and Europe participate. The Europeans give presentations on meteoroid and orbital debris protection for Columbus and the Hermes shuttle.

Ibid.

February 24-28

A conference called Technogenic Space Debris: Problems and Directions of Research is held at the IKI in Moscow. The Russian Defense Ministry, Russian Space Agency (RKA), and Russian Academy of Sciences sponsor the conference. The approximately 200 attendees include representatives from Japan, Europe, and U.S. companies. NASA debris experts were invited, but none could attend because the invitation came too late for them to prepare for the trip to Moscow. Papers are presented on the Soviet / Commonwealth of Independent States (CIS) Space Surveillance System (SSS), optical and radar systems used to compile the CIS satellite catalog, and other topics. Proposals are made for a dedicated phased array equatorial orbital debris radar, and for a joint U.S.-CIS tracking exercise using the Pion subsatellites (at this time scheduled for deployment in Spring 1992). A report on Cosmos 1275 reveals that the Russians believe a collision caused its breakup. The Russians also reveal that the Ekran 2 DBS broke up in GEO in 1978. The Russians report that condenser meteoroid detectors have flown on Soviet space stations since Salyut 1 in 1971, and that hypervelocity tests to 17 km/second were performed in support of the Vega Halley's Comet probes.

"Memorandum for the Record, Subj.: Technogenic Space Debris Conference," Kaman Sciences Corporation, March 9, 1992.

April German orbital debris researchers share with NASA radar images of orbital debris objects. The images were collected using the German FGAN radar system. Half the objects observed are not rotating. Presumably the breakups which produced them would have made them spin. The Germans also detect objects with slowing spin rates. Researchers suggest that interactions with Earth's magnetic field are stabilizing the debris pieces. Stable objects complicate optical observing because they do not present many sides as they move through the field of view of a telescope. It is thus more difficult to derive a mean value for shape and brightness for stable objects, as brightness depends on the viewing angle. This implies a new parameter to be taken into account in orbital debris albedo measurements.

Interview, David S. F. Portree with Karl Henize, June 8, 1992; interview, David S. F. Portree with Donald J. Kessler, June 23, 1993.

May 7-16 On the STS-49 mission, Endeavour recovers the Intelsat 6 satellite stranded in LEO 2 years earlier. The rescue is considered practical because of the enormous cost of building and launching a replacement (about $260 million) and the long lead-times before a replacement can be readied. NASA is to charge the Intelsat Organization $90-98 million for the rescue, depending on how much of the repair effort can be justified as SSF EVA practice. After the first 3-person EVA, Intelsat 6 is fitted with a kick stage and boosted to a GEO slot at 325.5 deg east, over the Atlantic.

May 15 The Space Debris Forum is held in Tokyo by JSASS and NEC Corporation. International experts on orbital debris provide overviews of several aspects of the issue.

May 25-June 3 After the U.K. proposed in an ITU consultative working group that all GEO satellites be boosted to 53 km above GEO at end of useful life, the U.S. Department of State and the FCC approached JSC to learn if the proposed separation distance was sufficient to safeguard GEO. The 53-km separation marks the outer boundary of the nominal migration of an object left to drift in a perfect geosynchronous orbit (period of 1436.1 minutes at 37,000 km). When JSC orbital debris team members declared the distance to be inadequate, pointing out that not all objects in GEO are in perfect geosynchronous orbits, the FCC and State Department asked Donald Kessler, Larry Jay Friesen of Lockheed Corporation at JSC, and Joseph Loftus to prepare the U.S. position paper on the issue. This was completed on April 15, 1992.

1992

Loftus attends the CCIR 4 meeting in Geneva May 25-June 3, where his draft of a recommendation for GEO satellite disposal is accepted by the CCIR and routed to the more than 180 member-states of the ITU for comment. It recommends that as little debris as possible be left in GEO, that the lifetime of objects in transfer orbits be minimized, and that transfer to graveyard orbits be carried out in such a way as to avoid blocking the radio communications of active satellites. A later draft (June 17, 1992 – CCIR document 4/141-E) adds the recommendation that an effective graveyard orbit for satellites be determined. While not bearing the force of international treaty or law, the recommendation would carry substantial weight if endorsed by a consensus of the countries in the ITU.

Interviews, David S. F. Portree with Joseph P. Loftus, Jr., August 9, 1993, and September 9, 1993; CCIR Document, USWP. 4A/9, "Management of Orbital Debris in the Geosynchronous Orbit"; CCIR Document 4A/TEMP/92(Rev. 2-E) and CCIR Document 4/141-E, "Draft New Recommendation, Environmental Protection of the Geostationary Orbit."

May 28

Douglas S. Adams, JSC Structural Mechanics Branch, and Karen Edelstein, JSC Structural Subsystem Manager for the Orbiter Forward Fuselage and Crew Module, respond to a request from Valerie Neal, Smithsonian Institution Department of Space History, for a piece of Shuttle window glass containing an impact pit. They offer a left-side windshield thermal pane from Columbia. It was pitted during the STS-35 mission in December 1990. The pit is one of the largest in the history of the Shuttle program. Edelstein and Adams call it "an excellent display piece." Columbia's crew noticed the pit while they were still in orbit. Most researchers favor impact by a fragment of an upper stage as the most probable cause. SEM analysis detected zinc and aluminum, neither of which normally occurs in meteoroids. The zinc signature was, however, atypical.

Letter, Douglas S. Adams and Karen Edelstein to Valerie Neal, May 28, 1992.

June

The GAO releases *Space Station: Delays in Dealing with Space Debris May Reduce Safety and Increase Costs*. In it, the GAO states that SSF was designed using the 1984 NASA orbital debris model, and that the model adopted by NASA in 1991 describes an orbital debris environment eight times worse. It reports that NASA ordered its centers to incorporate the 1991 model, but that no decisions had yet been made to implement the changes. The GAO cites January 1992 testimony by unnamed NASA engineers and debris experts, who stated that the new orbital debris model raises to 36 percent the risk of critical component shielding penetration in the first decade of operation. This would increase to 88 percent over SSF's projected 30-year lifetime. In its conclusions, the report states that difficult trade-offs between costs and risks will have to be made before the SSF CDR in 1993 (this was moved from 1991 after an SSF redesign). The GAO recommends that the CDR be delayed until "the 1991 model of the debris environment is fully implemented[,] changes to NASA's debris safety criteria are thoroughly assessed[,] and NASA develops a comprehensive strategy for dealing with debris." The GAO calls on NASA to develop shielding augmentation for small debris and other protection systems for medium and large debris.

Space Station: Delays in Dealing with Space Debris May Reduce Safety and Increase Costs, GAO, June 1992.

June In Moscow, the U.S. and Russia hold their third joint Orbital Debris Working Group meeting.

June At the Second LDEF Post-Retrieval Symposium 26 papers are presented on meteoroid and debris topics. Several researchers report that orbital debris caused 15 percent of the impacts on LDEF trailing surfaces – preflight modeling indicated these should be far fewer. The researchers state that this implies a population of debris in highly elliptical orbits 20-30 times larger than previously estimated. It probably originates in explosions of upper stages in geosynchronous transfer orbits. The largest LDEF impact feature is 5.25 mm across. No impactor is found, but researchers speculate that aluminum beads found in the crater are the remnant of an orbital debris impactor. Other debris found embedded in LDEF surfaces includes metal of many kinds, paint, and human waste.

> Michael Zolensky, "Summary of the Second LDEF Symposium," *LDEF Space Flight Environmental Effects Newsletter*, Vol. 3, No. 3, June 30, 1992; H. W. Dursch, *et al*, *Analysis of Systems Hardware Flown on LDEF – Results of the System Special Investigation Group* (NASA CR 189628), April 1992; *Second LDEF Post-Retrieval Symposium Abstracts* (NASA CP 10097), Arlene Levine, editor, 1992.

June 4 NASA and CNES representatives meet in Toulouse, France. The French ask to participate in the NASA ODERACS experiment.

> Minutes of Space Debris Meeting, NASA/CNES, Toulouse, France, June 4, 1992.

June 24-26 The University of Chicago marks the beginning of its second century with a Centennial Symposium called The Preservation of Near-Earth Space for Future Generations. Because 1992 is the International Space Year, an important focus is international cooperation on orbital debris. Representatives from the space establishments of Europe, China, India, Japan, France, Russia, and the U.S. report on their orbital debris policies and methods.

> "Debris Meeting in Chicago," *Orbital Debris Monitor*, Vol. 5, No. 4, October 1, 1992, pp. 12-19.

June 25-July 9 Columbia orbits Earth for nearly 14 days on the first Extended Duration Orbiter (EDO) mission (STS-50). The oldest orbiter spends nearly 10 days with its nose toward space and its payload bay facing its direction of motion. After landing, NASA and Lockheed engineers discover 51 hypervelocity impact damage sites on the windows, reinforced carbon-carbon wing leading edges, and radiator panels. The Thermal Protection System (the bulk of the surface of the orbiter) is not examined because it normally sustains from 50-200 low-velocity debris strikes during launch and landing, and there are insufficient resources available to distinguish this damage from hypervelocity impact damage. SEM analysis shows that 35 percent of the hypervelocity impact damage sites contain orbital debris objects (paint flecks, stainless steel, aluminum, and titanium). Meteoroids caused 25 percent of the damage sites. The remaining 40 percent are of unknown origin. Six craters are found in five of the orbiter windows, including the deepest found in the history of the Shuttle program (0.57 mm). It was caused by a titanium-rich particle. Three windows are replaced at a cost of $50,000 each. Up to

1992

STS-45 (March 24-April 2, 1992) Shuttle windows suffered impact damage 49 times, resulting in 25 discarded thermal glass panes.

> Eric Christiansen, *et al*, "Assessment of High Velocity Impacts on Exposed Shuttle Surfaces," presented at the First European Conference on Space Debris, Darmstadt, Germany, April 5-7, 1993; Memorandum, "Orbiter Window Damage," Karen Edelstein to Joseph P. Loftus, Jr., April 22, 1992; "New Shuttle Flight Rule," *Orbital Debris Monitor*, Vol. 5, No. 4, October 1, 1992.

July 31-August 8 The Space Shuttle Atlantis deploys the European Retrievable Carrier (Eureca) on the STS-46 mission. It carries the Timeband Capture Cell Experiment (TiCCE) from the University of Kent (England), which collects micron-sized particles in "Space Station-type" orbits. The device unrolls a tape at a steady pace, exposing new sections (timebands) to space every 2-3 days over 9 months. This permits the time of impact events to be determined. Eureca was recovered by the Space Shuttle Endeavour on the STS-57 flight in June 1993.

> T. J. Stevenson, "Eureca TiCCE – A Nine-Month Survey of Cosmic Dust and Space Debris at 500 km Altitude," *Journal of the British Interplanetary Society,* Vol. 41, 1988, pp. 429-432.

August 10-12 John Vedder, Jill Tabor, and Diane Walyus, McDonnell Douglas Space Systems Company, describe the orbital debris problems of future Nuclear Electric Propulsion (NEP) spacecraft on Moon and Mars missions. Such vehicles would accelerate slowly, spending weeks or month spiraling slowly outward from Earth before attaining escape velocity. The researchers determine that the greatest danger exists in LEO, and that 80 percent of the total hazard is in the 800-1100-km altitude region. They recommend spending as little time as possible in LEO, and that the long axis of an NEP vehicle be kept parallel to its direction of motion so it presents a smaller target to debris.

> John Vedder, *et al*, "Orbital Debris Hazard for Nuclear Electric Propulsion Earth-Escape Trajectories," *1992 AIAA/AAS Astrodynamics Conference, A Collection of Technical Papers*, pp. 165-175.

August 15 NASA Administrator Daniel Goldin writes to Ralph Carlone, Assistant Comptroller General of the GAO, in response to the GAO report *Space Station: Delays in Dealing with Space Debris May Reduce Safety and Increase Costs*. Goldin states that the SSF orbital debris model adopted in 1991 was developed by NASA and is accepted by the international space community. He says NASA will check and upgrade the model as appropriate, using data from its ongoing debris measurement program. Any proposed changes will undergo scrutiny by an independent review team before being implemented. Goldin says that the "safety of humans in space is our highest priority." He states that the 1993 CDR will not be delayed.

> Letter from Daniel Goldin, NASA Administrator, to Ralph Carlone, Assistant Comptroller General, GAO, August 15, 1992.

August 19 The RKA launches the Vostok-based Resurs F-16 imaging film return spacecraft. It carries a Beryllium 7 collection experiment provided by the U.S. Air Force Space Test Program and the Naval Research Laboratory. Resurs F-16 also carries the Pion 5 and Pion 6 subsatellites, metal spheres approximately

60 cm in diameter. Resurs F-16 releases them on September 4, just before it returns to Earth. They are tracked as they decay from orbit. Pion 6 reenters on September 24, and Pion 5 reenters the next day. In 1989 the U.S.S.R. conducted two similar missions to help update their space tracking capabilities. NASA's planned ODERACS experiment is similar in principle to the Russian experiments.

"Russian Satellite Deploys First U.S. Military Test," *Aviation Week & Space Technology*, August 31, 1992, p. 23; *TRW Space Log 1992*, p. 54.

August 19 The JSC MOD Orbit Flight Techniques Panel holds its 131st meeting, at which representatives of Rockwell Corporation (builder of the Shuttle orbiters) and Donald Kessler and Eric Christiansen present results of a study of orbital debris damage risks associated with certain Shuttle flight attitudes. The study indicates that "the -ZVV [payload bay forward] attitude. . . is the worst attitude from a catastrophic damage perspective. The risk was between three and five times greater. . . than the best attitude which is -ZLV, -XVV (bay down, tail forward)." The study also finds that the risk of damage to the Shuttle radiators, which are deployed from the inside of the payload bay doors, is 16 times greater in -ZVV than in -ZLV. Damage to windows is 20 times more likely in -ZVV with the +XVV (nose forward) attitude almost as risky (fig. 7). These results are reinforced by examination of Columbia's surfaces after the STS-50 EDO flight. In October 1992 the Orbit Flight Techniques Panel develops Flight Rule 2-77, "Attitude Restrictions for Orbital Debris," which states that use of the -ZVV and +XVV, +XLV (payload bay up) or ±YLV (payload bay out of plane) attitudes will be minimized during preflight mission planning and during the mission. It further states that the "-ZLV attitude will be the normal orbiter attitude unless payload or orbiter requirements dictate otherwise." The rule calls for orbiter preflight planning to be tailored so the orbiter will spend fewer than 48 hours of cumulative time during a mission in the higher-risk attitudes. Exceptions will be made on the basis of flight requirements and documented in the annex to the flight rules for a given flight. In addition, MOD adds section 4.2.4.2., "Altitude Adjustment Strategy," to its "Space Shuttle Operational Flight Design Standard Ground Rules and Constraints." Section 4.2.4.2. states that mission designs will be selected which keep Shuttle orbital altitudes below 320 km, provided that such altitudes are "compatible with mandatory payload constraints and other high priority objectives." In addition, when the mission activities which require the orbiter to operate above 320 km conclude, the orbiter should be moved to a lower orbit if propellant supply permits.

"NASA Johnson Space Center Flight Rules," Flight Rule 2-77, pp. 2-80a - 2-80b; interview, David S. F. Portree with Michael F. Collins and J. Steven Stich, August 17, 1993; "Space Shuttle Operational Flight Design Standard Ground Rules and Constraints" (NSTS-21075 Rev. A), Level B, Change 6, April 30, 1993, 4.2.4.2.

August 20-21 An ESA-Russia Workshop on objects in GEO is held at ESOC.

Letter, Walter Flury, ESA ESOC, to Joseph P. Loftus, Jr., NASA JSC, September 29, 1992.

August 27 The International Academy of Astronautics (IAA) Ad Hoc Expert Group of the Committee for Safety, Reliability, and Quality circulates to its members a

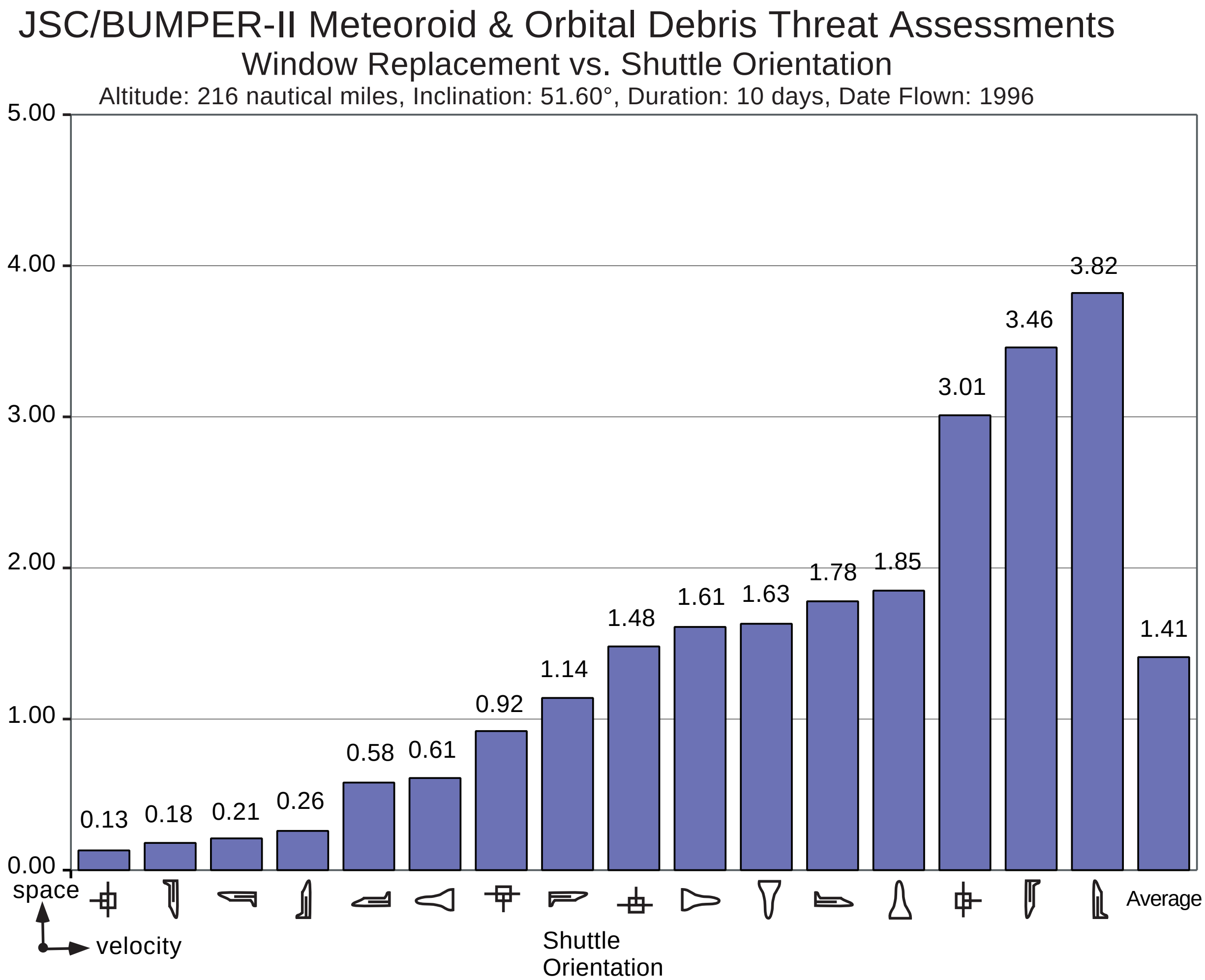

Figure 7.

More than 70 Shuttle windows have had to be replaced (as of January 1998) because of impact damage since the Shuttle program began in 1981. This chart above, which is based on calculations using the BUMPER II computer program devised by the Space Science Branch, JSC, shows the number of orbiter window replacements expected for various attitudes. The tail-forward, cargo bay down (that is, away from the cold of space) attitude protects the windows and is preferred for thermal reasons, but increases risk to the wing leading edges. The nose-down, belly-forward orientation is preferred when astronauts conduct spacewalks in the Shuttle cargo bay. The cargo bay forward, nose-up attitude increases risk to Shuttle windows, wing leading edges, and vital components, such as the radiator panels on the inside of the cargo bay doors, and tanks under the cargo bay floor. The attitude of the orbiter docked to the International Space Station is nose-up, belly forward.

draft copy of "A Position Paper on Orbital Debris." The Ad Hoc Expert Group includes representatives from the U.S., Russia, Japan, Germany, ESA, and Czechoslovakia. The position paper calls for internationally accepted debris controls, international coordination meetings, educational efforts, space law specifically governing orbital debris, a forum to coordinate multi-lateral agreements, and other measures. The position paper has three objectives – "to make clear how significant and severe the continued deposition of orbital debris into the near-Earth environment is to the future use of space for all mankind, to provide some clear guidelines as to how the international community might wish to proceed in order to combat this growing space environmental hazard, and to extend discussion of the debris issue by other international groups to exercise the techniques and dialog necessary to begin to formulate international agreements on this topic."

> "A Position Paper on Orbital Debris Compiled by an Ad Hoc Expert Group of the International Academy of Astronautics, Committee on Safety, Rescue, and Quality," August 27, 1992 (draft).

August 28-September 5 The World Space Congress convenes in Washington, D.C. In conjunction with the Congress, papers on orbital debris issues are presented and orbital debris meetings are held.

September Nicholas Johnson and Darren McKnight, Kaman Sciences Corporation, J. M. Cherniyevski of the Center for Program Studies of the Russian Academy of Sciences, and B. V. Cherniatiev, Energia Scientific Production Association, meet to determine the probable cause of five debris events linked to the Proton Block DM (fourth stage). They occurred between 1984 and September 1992. Through "unprecedented international cooperation," the team determines that two small (56-kg dry mass) auxiliary motors used to settle fuel in the Block DM after weightless coast (ullage motors) are responsible. They are routinely ejected when the Block DM stage ignites for the final time. Remaining in each auxiliary motor at ejection are 10-40 kg of hypergolic propellants. The international team decides that an explosion occurs when a thin interior wall ruptures, allowing the fuel and oxidizer to mix. Additional debris-producing explosions are likely because the Proton launch vehicle is commonly used. Thirty-four auxiliary motors remain in orbit from Russian global positioning navigation system (GLONASS) launches alone.

> B. V. Cherniatiev, *et al*, "Identification and Resolution of an Orbital Debris Problem with the Proton Launch Vehicle," *Orbital Debris Monitor*, Vol. 6, No. 1, January 1, 1993, pp. 7-9.

September 3-4 An orbital debris coordination meeting is held in Washington, D.C. between NASA and the TUBS.

September 5-6 The Fourth Meeting of the Joint U.S.-Russia Orbital Debris Working Group is held in Washington, D.C., in conjunction with the World Space Congress. The countries provide each other with copies of their satellite catalogs. An agreement to exchange modeling results is reaffirmed. The Russians propose that ESA participate in orbital debris talks with NASA and the Russian KOSMOS organization. The sides also discuss a joint debris-tracking radar. The Russians tell NASA that Walter Flury of ESA and Nicholas Johnson, Senior Scientist at Kaman Sciences, will participate in the Pion subsatellite tracking experiment. The question of NASA participation is left unresolved. Eugene Stansbery is made point-of-contact between the U.S. and Russia for the Pion experiment.

Minutes of the Fourth Meeting of the U.S./Russian Orbital Debris Working Group, September 5-6, 1992.

September 28-October 5

Lubos Perek, Astronomical Institute, Czechoslovak Academy of Sciences, presents "Must Space Missions Be Beneficial?" at the 35th Colloquium on the Law of Outer Space, Washington, D.C., a paper describing novel space activities and their implications. He refers to the Outer Space Treaty (1967), which calls for space to be used for the benefit of all countries. He points out, however, that the potential exists for conflicts of interest over what is beneficial and what is not. What one country, agency, company, or community of interest calls "harmful interference" (the term used in Article IX of the treaty), another might consider beneficial space activity. He uses the example of the conflict between the satellite launching industry and the community of astronomers over the effects on optical astronomy of disused satellites. Perek then describes several other projects, including

- A proposed ARSAT (Art Satellite) which would have commemorated the centennial of the Eiffel Tower in 1989. It would have consisted of 100 inflatable spheres, each 6 m across, linked by cables to form a "ring of stars" as large as the full moon.

- Celestis Space Services' Urnsat scheme to launch cremated human remains into orbit. Perek writes that "[t]he generations succeeding those cremated and launched would know that their ancestors are still moving overhead and posing a hazard to the lives of astronauts. What a cruel and unusual punishment beyond anything Dante Alighieri could think of for his *Comedia Divina*!"

- Lunetta, Powersoletta, Agrisoletta, and Biosoletta, which would reflect sunlight over large areas of the Earth from orbit for a variety of beneficial purposes. Perek points out that despite detailed technical studies of these systems in the late 1970s, little thought was given to their possible environmental effects, and none to their effects on astronomy.

- Solar Power Satellite (SPS) systems of the type supported by Christopher Kraft in the mid-to-late 1970s in GEO. Perek points out that these were studied for their environmental effects (in part by the EEO under Andrew Potter at JSC). Each SPS would be as bright as Venus at its brightest. The combined brightness of many SPS would interfere with optical astronomy, and SPS in GEO would contribute to GEO crowding.

Perek states that "[t]he real danger of such projects is not in proposing them because a grain of truth may be in any product of human imagination. The danger lies with official agencies reviewing and approving space projects on formal grounds only without taking into account all implications and without realizing that the consequences of their decisions may be with us much longer than anything else that mankind ever produced."

Lubos Perek, "Must Space Missions be Beneficial?" *Proceedings of the 35th Colloquium on the Law of Outer Space*, Washington, AIAA, 1993, pp. 303-306.

October 20-21 The Eighth Coordination Meeting on Orbital Debris, NASA / ESA / Japan, is held at JSC. Naoki Sato of NASDA describes the status of JEM debris protection development, and Helmut Heusmann briefs the meeting on Columbus debris protection. Christiansen and Crews describe SSF shielding. H. Klinkrad and R. Jehn of ESA tell the meeting that analysis of the decay of the Pion 5 and 6 subsatellites released by the Russian Resurs F-16 satellite on September 4 has improved decay predictions.

Minutes of the Eighth Coordination Meeting on Orbital Debris, ESA/NASA/Japan, October 20-21, 1992; Memorandum, Andrew E. Potter to Distribution, January 20, 1993.

October 29 *Aerospace Daily* reports that the amount of EVA assembly time planned for SSF has been reduced, in part because of the orbital debris hazard to spacewalkers. The article refers to statements by William Raney, NASA Special Assistant for Space Station. U.S. spacesuits have a pressurized inner suit and an outer thermal garment which provides protection against meteoroids and orbital debris to about 1 mm in size. Russian suits are of generally similar design.

Aerospace Daily, October 29, 1992.

November An LDEF II planning briefing is held at JSC. Michael Zolensky, Office of the Curator (of Lunar Samples), Solar System Exploration Division, JSC, describes lessons learned from working with the first LDEF. Zolensky suggests that the next LDEF have improved capabilities for gathering data on meteoroids and orbital debris. He states that the same care used in handling LDEF experiments during removal should be used when installing them before launch. No anodized aluminum surfaces should be used, because they contain nonmetallic impurities which complicate analysis. In addition, collection systems which permit accurate impact time determination should be included.

Memorandum, Michael Zolensky to LDEF II meeting attendees, December 1, 1992.

November The *International Journal of Impact Engineering* publishes an article by Eric Christiansen and Justin Kerr, JSC, titled "Mesh Double-Bumper Shield: a Low-Weight Alternative for Spacecraft Meteoroid and Orbital Debris Protection." The MDB shield was first described by Christiansen in a 1990 paper presented at the AIAA / NASA / DoD Orbital Debris Conference. They state that, "The MDB shield was developed to demonstrate that a Whipple shield could be 'augmented'. . . to substantially improve protection by adding a mesh. . . in front of the Whipple bumper and inserting a layer of high strength fabric between the second bumper and the wall." Research in the JSC HIT-F indicates that by using the MDB design a 30-70 percent weight savings can be achieved without a corresponding loss in level of protection.

Eric Christiansen and J. H. Kerr, "Mesh Double-Bumper Shield: A Low-Weight Alternative for Spacecraft Meteoroid and Orbital Debris Protection," *International Journal of Impact Engineering*, November 1992; Eric Christiansen, "Advanced Meteoroid and Debris Shielding Concepts," AIAA paper 90-1336, *Orbital Debris: Technical Issues and Future Directions* (NASA CP 10077), Andrew E. Potter, editor, September 1992.

November 8

Cosmos 1508 is a 550-kg, 1.8-m octagonal satellite. It was launched into a 394-km-by-1943-km, 82.9-deg inclination orbit on November 11, 1983, to carry out a minor military mission (possibly radar calibration, air density measurements, electronic monitoring, or technology demonstration). On this date the disused satellite passes within 300 m of the Mir space station, which at this time is home to Soyuz-TM 15 cosmonauts Anatoli Solovyov and Sergei Avdeyev. This is the closest known conjunction between an uncontrolled satellite and a manned spacecraft.

TRW Space Log 1992, p. 28; Jos Heyman, *Spacecraft Tables 1957-1990*, p. 136; letter, Nicholas L. Johnson to Joseph P. Loftus, Jr., August 17, 1993.

December

The British company Sira, working with Unispace and the Royal Greenwich Observatory, completes a feasibility study as part of an ESA contract. The company calls the study “the first step in the development of instruments to detect and characterize debris in Earth orbit.” It proposes ground-based and space-based optical, infrared, and radar instruments for monitoring LEO and GEO. The system would collect data on the sizes, shapes, densities, albedos, spin rates, altitudes, and orbital inclinations of debris pieces. The four-phase development program would require 3 years from inception to launch or installation.

Tim Furniss, “Spying on Space Debris,” *Flight International*, December 23, 1992-January 5, 1993, p. 36.

December 2-9

On the STS-53 Space Shuttle flight, the orbiter Discovery carries the ODERACS experiment. ODERACS comprises six spheres of different diameters, made of aluminum or steel, which are to be deployed from a Get-Away Special (GAS) canister in the payload bay. The experiment is meant to provide calibration targets in LEO for ground-based radar and optical systems. Three of the spheres are highly polished (“specular”) and three are sand-blasted to a dull finish (“diffuse”) so they can serve as Bond albedo (reflectivity) calibration targets. After deployment at 256 km, the spheres will be tracked using the Haystack radar and other U.S. radar and optical tracking systems. The German FGAN radar and French, Japanese, Russian, and Chinese tracking systems will also take part. Through no fault of its NCSU student designers or the program staff under John Stanley, the door on the GAS canister fails to open. The experiment is not powered up and the spheres cannot deploy. The ODERACS experiment is subsequently rescheduled for flight on the STS-60 mission in early 1994. On flight day 6 Discovery avoids a large piece of orbital debris by changing velocity by 0.7 m / second with an 8-second burn using the +X (aft) thrusters.

“STS-53 Mission Report,” NASA JSC, February 1993, p. 4; “Orbital Debris Radar Calibration Spheres” (copies of transparencies), June 15, 1993; interview, David S. F. Portree with John Stanley, June 21, 1993.

December 17-18

A sixth Block DM auxiliary motor explodes. The ullage motor was part of the Proton launch vehicle which inserted the Soviet Gorizont 17 domestic communications satellite into GEO in 1989. Between 75 and 100 trackable pieces are produced.

B. V. Cherniatiev, *et al*, “Identification and Resolution of an Orbital Debris Problem with the Proton Launch Vehicle,” *Orbital Debris Monitor*, Vol. 6, No. 1, January 1, 1993, pp. 7-9.

1993

End of year launches reaching Earth orbit or beyond (since 1957)	3574
End of year satellites (objects in orbit)	7585

January 10-14 In a paper presented at the Tenth Symposium on Space Nuclear Power and Propulsion, planners of space nuclear power system operations state that it is necessary to take into account the possibility of orbital debris collisions with space nuclear power systems.

J. A. Sholtis, *et al*, “U.S. Space Nuclear Safety: Past, Present, and Future,” presented at the Tenth Symposium on Space Nuclear Power and Propulsion, Albuquerque, New Mexico, January 10-14, 1993.

January 27-28 JSC holds a meeting to evaluate in light of new Haystack radar data the SSF orbital debris model NASA adopted in 1991. Representatives from XonTech, JSC, Kaman Sciences, MSFC, AFSPACECOM, and other organizations attend the meeting. They reach general consensus that

- For the sizes of interest to SSF shielding designers (smaller than 3 cm), the new Haystack observations fall within the expected uncertainty of the 1991 model.

- For objects in the larger “mid-range and collision avoidance regime,” Haystack provides “convincing evidence that the size [of the population] of these objects has been overestimated. . . perhaps by a factor of two.” However, this has little impact on SSF engineering considerations.

- The uncertainty in projecting the future orbital debris environment remains as high as before Haystack data became available, because “previously unmodeled sources of debris appear to be required to fully understand the Haystack data.” The participants conclude that Haystack data should be gathered over a full solar cycle, and that the times and operative modes of the radar, as agreed upon by NASA and USSPACECOM, might require changing.

The participants recommend that the SSF program continue to use the orbital debris environment model adopted in 1991. They acknowledge, however, that some Haystack data point already to a need for the model’s eventual refinement. They resolve to continue their critical examinations of the existing model, using data not only from the Haystack radar, but also from the LDEF, the Goldstone radar, and USSPACECOM.

Memorandum, Donald J. Kessler to George Levin, NASA Headquarters, February 6, 1993.

February 4 The Russian Progress-M 15 cargo spacecraft undocks and backs away from the Mir space station complex after 3 months docked at its forward port. Progress-M 15 deploys Znamya (Banner), a 20-m dia solar reflector, from its nose. It is billed as the world's first solar sail, but during this test it is used as a soletta, reflecting sunlight down toward the Earth. The reflector completes four orbits of the Earth in 5 hours, passing over Spain, France, Austria, Poland, Belarus, Ukraine, Russia, Kazakhstan, China, Japan, and portions of South America. It is then detached from Progress-M 15. It remains visible, tumbling and sparkling, for 24 hours after the test, and is seen widely in Canada. The mission manager for the Znamya experiment, Vladimir S. Syromiatnikov, NPO Energia company, reports that the beam of light was more diffuse than anticipated. He says, however, that the test was a success, and that "I believe we can persuade our leaders to perform a second test very soon." The area on the ground lit by Znamya at any one time measured 4 km across.

Peter B. de Selding, "Russians Deploy Reflector, Test Illuminating Idea," *Space News*, February 8-14, 1993, pp. 3-21.

March

Researchers at the HIT-F complete tests begun in November 1992 on the Stuffed Whipple meteoroid and orbital debris protection system (fig. 8). The Stuffed Whipple, a hybrid of the MDB and MSS designs, is designed to augment the baseline SSF Whipple shield. It comprises a layered blanket of aluminum mesh, Nextel ceramic fabric, and Kevlar polymer, which would be placed between the aluminum Whipple bumper and the aluminum backplate (the SSF module pressure hull). Hypervelocity impact tests show the Stuffed Whipple can meet or exceed the SSF orbital debris design requirements.

Interview, David S. F. Portree with Eric Christiansen, May 11, 1993.

March

The Space Debris Study Group of JSASS releases its final report. It describes shuttle and spacesuit debris protection, impact tolerant designs, and debris crater formation. It cites many ESA and NASA authors.

Space Debris Study Group Report, Space Debris Study Group, JSASS, March 1993.

March

The Midcourse Space Experiment (MSX) satellite is an SDIO vehicle. The Space-Based Visible Experiment Principal Investigator team, lead by Michael Gaposchkin of MIT-LL, is responsible for the satellite's many optical experiments. This month Faith Vilas and Phillip Anz-Meador at JSC complete designs for three MSX experiments with application to orbital debris studies. The Debris Detection and Characterization experiment will search the region around three fragmentation events – one each for LEO, GEO, and a highly eccentric orbit. The Ram / Anti-Ram Debris Observations experiment will search for debris ahead of and behind MSX, providing data for search strategies for collision avoidance by spacecraft and space stations in Earth orbit. The Resident Space Object Fragmentation experiment will observe a fragmentation event in LEO 24-48 hours after it is spotted by ground-based USSPACECOM tracking systems, with the aim of characterizing the fragments produced. MSX orbital debris experiments are constrained by the requirements of the many other experiments on the satellite. For this reason they will be aimed at targets of opportunity – they will not monitor the debris

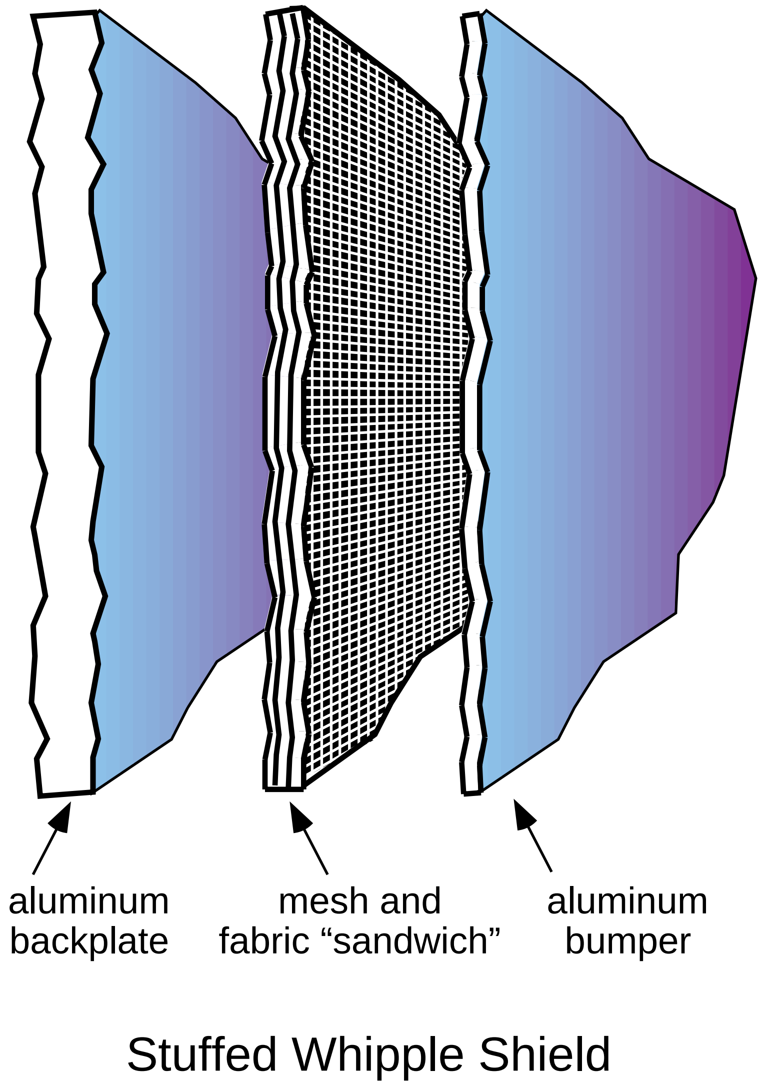

Figure 8.

The Stuffed Whipple is a hybrid of the Multi-Shock Shield and Mesh Double Bumper protection systems (see fig. 6). It is designed to augment the baseline Space Station Freedom Whipple Bumpers. A “blanket” comprising multiple layers of aluminum mesh and ceramic fabric would be unrolled between the aluminum bumper and the backplate (the spacecraft hull), probably after Freedom deployment in orbit. NASA would thereby avoid any Space Station deployment delay caused by a need to redesign its existing orbital debris protection. In addition, the blanket could be rapidly tailored to take into account possible refined assessments of the debris environment. The blanket would further break up impactors and capture most impactor and bumper pieces before they could strike the spacecraft hull.

environment. The MSX satellite is scheduled for launch in August 1994. Its mission is projected to last 4-5 years.

Note, Faith Vilas to Davis S. F. Portree, December 6, 1993; interview, David S. F. Portree with Faith Vilas, December 7, 1993.

April

In the face of a mounting U.S. federal budget deficit, President William Clinton calls on NASA to redesign SSF to reduce its costs. With the selection of Option Alpha, the U.S. Space Station becomes smaller and more compact – in theory a smaller target for orbital debris. In practice, Option Alpha may contain greater risks as it lacks the "shadowing" common in earlier SSF designs. That is, the critical components, such as crew modules, are not as shielded against orbital debris impacts by less critical or more durable components as they were in the SSF configurations. Late in the summer the U.S. and Russia agree to combine the U.S. station and the planned Russian Mir 2 station. The new joint station will be placed in a 51.6-deg inclination orbit so it is accessible to both U.S. and Russian spacecraft. Orbital debris poses a 15-20 percent greater risk for a vehicle in a 51.6-deg inclination orbit than for one in a 28.5-deg orbit (the original SSF inclination). If they are to operate at SSF altitude, Mir 2 components might require shielding augmentation to bring them up to the standards adopted by the U.S., Japan, and Europe for SSF meteoroid and orbital debris shielding. A rigorous assessment will be required to determine the level of augmentation needed. At lower Mir 1 altitudes, such shielding is not as important. Mir 1 operates within the "sensible atmosphere," meaning that debris approaching the station is bound for rapid decay. This reduces the chances that its path will intersect the station's on a future orbit.

Interview, David S. F. Portree with Donald J. Kessler, September 8, 1993; interview, David S. F. Portree with Joseph P. Loftus, Jr., September 9, 1993.

April 2-3

Representatives of ESA, NASDA, RKA, and NASA – in short, all the major space powers – meet in Darmstadt for multilateral talks. The four agencies agree to exchange technical information and experience in the context of the Inter-Agency Space Debris Coordination Committee (IADC). Although the IADC is new, this is designated the 9th IADC meeting. IADC grew from previous bilateral and multilateral meetings between NASA and the other agencies formed after the 1986 Ariane V16 breakup and the 1989 Interagency Group (Space) Report.

April 5

NASA Management Instruction (NMI) 1700.8, "Policy for Limiting Orbital Debris Generation," is published. It 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 two-page document, which remains effective through this date in 1997, is the first NASA-wide binding guidance on orbital debris mitigation. The NMI fulfills a requirement of the U.S. National Space Policy (February 11, 1988).

"Policy for Limiting Orbital Debris Generation," NASA Management Instruction 1700.8, April 5, 1993; *Guidelines and Assessment Procedures for Limiting Orbital Debris*, NSS 1740.14, August 1995.

April 5-7 ESA holds the First European Conference on Space Debris in Darmstadt. More than 250 orbital debris researchers from the U.S., China, Russia and the other CIS countries, Japan, India, and a dozen other states attend. In a joint statement, they conclude that the more than 7000 objects in Earth orbit do not pose an immediate danger to human space activity, though measures must be taken to keep the hazards from growing beyond safe limits. Because it is neither technically nor economically feasible to clean up space, action must be taken to prevent the creation of new debris. Furthermore, they declare that any action can be successful only if it is implemented through international cooperation. Victor J. Slabinski, of the Intelsat organization, presents a paper called "Intelsat Satellite Disposal: Orbit Raising Considerations," which supports the position taken in the U.S. CCIR position paper of April 15, 1992, as well as the draft recommendation written by Loftus and submitted at CCIR 4 on May 29, 1992.

Ibid; "First European Space Debris Conference," *Spaceflight*, Vol. 35, June 1993, p. 185; Victor J. Slabinski, Intelsat Spacecraft Disposal: Orbit Raising Considerations," presented at the First European Conference on Space Debris, Darmstadt, Germany, April 5-7, 1993.

June The U.S. Congress inserts language into the FY 1994 NASA Authorization Bill calling for U.S. government action on orbital debris. Specifically, section 309 mandates that "[t]he Office of Science and Technology Policy, in coordination with the National Aeronautics and Space Administration, the Department of Defense, the Department of State, and other agencies as appropriate, shall submit a plan to Congress within one year after the date of enactment of this Act for the control of orbital debris." Section 309 also calls for the plan to include "launch vehicle and spacecraft design standards and operational procedures to minimize the creation of new debris" and "a schedule for the incorporation of the standards into all United States civil, military, and commercial space activities." Finally, it states that the plan "shall include a schedule for the development of an international agreement on the control of orbital debris."

FY 1994 NASA Authorization Bill, August 4, 1993 version, p. 25

June Zhang Wen Xiang and Liao Shao Ying of the Chinese Launch Vehicle System Design and Research Institute announce that the upper stage of the Long March 4 rocket is being redesigned to make it less likely to explode in orbit.

Z. W. Xiang and L. S. Ying, "Analyzing the Cause of LM-4(A)'s Upper Stage's Disintegration and the Countermeasure," presented at the International Space Conference of Pacific Basin Societies, Shanghai, China, June 6-9, 1993.

June During the Plenary Session of the U.N. COPUOS, the U.S. initiates a consensus decision to place the orbital debris issue on the agenda of the U.N. COPUOS Scientific and Technical (S & T) Subcommittee meeting scheduled for February 1994.

Interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997.

June 1 The *Monthly Notices of the Royal Astronomical Society* publishes a letter by Martin Beech and Peter Brown, graduate students at the University of Western Ontario, on the possible danger of the 1993 Perseid meteor stream to

Earth-orbiting satellites. They report that the geometry of Earth and the comet which produces the Perseid stream, Swift-Tuttle, is such that meteoroid flux could attain “storm” levels in 1993.

Interview, David S. F. Portree with Mark Matney, November 21, 1997; “Impact Possibilities on Artificial Satellites for the 1993 Perseid Meteor Stream,” *Monthly Notices of the Royal Astronomical Society*, Vol. 262, L35-36 (1993).

June 21-July 1 On the STS-57 mission, the Space Shuttle Endeavour orbits Earth for nearly 10 days. It carries in the forward half of its payload bay the first Spacehab module, a commercial space facility. Endeavour retrieves the Eureca satellite, which carries the TiCCE, a British-built device for collecting orbital debris particles. The MCC delays a planned maneuver by 45 minutes to avoid a space object predicted to pass near the orbiter’s 2-km-by-5-km-by-2-km maneuver box. Endeavour’s orbit is lowered after Eureca retrieval in accordance with Flight Design Standard Ground Rule 4.2.4.2. Eureca meteroid and orbital debris analysis begins in July.

Interview, David S. F. Portree with Michael F. Collins and Steven Stich, August 17, 1993; “Conjunction Summary for STS-26 through STS-85,” memorandum with attachments, Steven Stich, DM32/Lead, Orbit Flight Dynamics Group, September 17, 1997.

June 22 Larry Petro of the Space Telescope Science Institute issues a recommendation that HST be oriented to shield sensitive systems and present a minimal cross-section during the upcoming passage of Earth through the Perseid meteor stream. He cites the Brown and Beech letter in the *Monthly Notices of the Royal Astronomical Society*. The institute adopts Petro’s recommendation in July.

Interview, David S. F. Portree with Mark Matney, November 21, 1997; “The Perseid Meteors - 1993, a Chronology of Our Involvement,” presentation materials, no date.

July 12-13 ESA and RKA meet at TsNIIMash, outside Moscow, to exchange and review information on orbital debris. V. I. Lukyashchenko is meeting chair, and many important figures in European and Russian orbital debris work attend. The sides review the draft IADC Terms of Reference. Other presentations cover ESA’s log of GEO objects, Russian debris models, and debris mitigation techniques of the Proton, Zenit, and Ariane launchers. Participants visit TsNIIMash’s light-gas gun used for hypervelocity impact experiments.

“Notes on the RKA/ESA Space Debris Coordination Mtg., Tsniimash, Kaliningrad/Moscow, Russia,” July 12-13, 1993.

July 29 On this date officials of the Space Shuttle Program at NASA JSC teleconference with other NASA centers to discuss the possible threat the Perseid meteor stream poses to STS-51. The meeting was called by Shuttle Program Manager Brewster Shaw at the urging of Joseph Loftus. Discovery is scheduled to be in orbit August 11-12, during a possible meteor storm in which as many as 100,000 meteors / hour could strike Earth. According to Donald Kessler, in the worst case the risk of a meteoroid impact damaging the Shuttle could double during the possible Perseids storm, from 1 in 1000 to 1 in 500. Storm meteoroids averaging 0.1 mm in diameter could impact at greater than 70 km / second. Orbital debris moves at 10-12 km / second and normal micrometeoroids move at an average speed of 20 km / second. On July

30 Space Shuttle Program management elects to delay the STS-51 launch until after the peak of the Perseids shower.

Interview, David S. F. Portree with Mark Matney, November 21, 1997; "The Perseid Meteors - 1993, a Chronology of Our Involvement," presentation materials, no date; "Approaching meteors scuttle shuttle launch," *Houston Chronicle*, July 31, 1993, p. 14A.

August NASDA forms an in-house space debris working group.

August 11-12 Perseids storm occurs, though not with the ferocity originally predicted. Nevertheless, cosmonauts on Mir report 100 significant hits on the station. ESA's experimental Olympus satellite, launched into geosynchronous orbit on July 12, 1989, began to tumble late on August 11, just prior to the predicted peak. The precise cause of the satellite's failure is unknown. Olympus was experiencing technical problems prior to this, but an impact is deemed a possible "straw that broke the camel's back." A worldwide monitoring effort accumulates data on the effects of the stream to predict and manage responses to future events.

Interview, David S. F. Portree with Mark Matney, November 21, 1997; "Olympus and the Perseids - An Encounter?" R. Douglas Caswell, Olympus Spacecraft Manager, presentation materials, NASA Leonid Meteor Shower Working Group Meeting, May 8-9, 1997.

August 11-13 The Committee on Space Debris of the National Research Council's Commission on Engineering and Technical Systems, Aeronautics and Space Engineering Board, meets for the first time in Washington, D.C. The meeting launches the study effort which culminates in the NRC's report *Orbital Debris: A Technical Assessment* (1995). The purpose of the study is to

- characterize the debris environment
- "project how this environment might change in the absence of new measures to alleviate debris proliferation"
- "examine ongoing alleviation activities and existing space law pertaining to the debris problem"
- "explore measures to address the problem, including further research on debris monitoring and modeling, and methods to minimize debris generation"
- develop recommendations on technical and engineering methods to address the problems of debris proliferation

Retired TRW chief of engineering George Gleghorn is study chair. International orbital debris experts form the study's steering committee, including Walter Flury, ESA/ESOC; Nicholas Johnson, Kaman Sciences; Donald Kessler, NASA JSC; Dietrich Rex, TUBS; Susumu Toda, National Aerospace Laboratory of Japan; and Stanislav Veniaminov, SRC Kosmos.

Interview, David S. F. Portree with Nicholas Johnson, November 15, 1997; interview, David S. F. Portree with Donald Kessler, November 25, 1997; *Briefing Book: Committee on Space Debris Workshop*, November 18-23, 1993.

September Cosmic Background Explorer (COBE) was launched in November 1989. In January the satellite began producing debris objects non-catastrophically (that is, without an obvious debris-producing event). By this month, with the satellite in a 900-km circular orbit at 99 deg of inclination, U.S. Space Command catalogues 33 debris pieces. The debris decays from orbit more rapidly than the spacecraft, rocket body, and two pieces of operational debris. One theory is that the new debris objects are fragments of insulation; however, COBE experiences neither temperature changes nor other obvious changes in its systems, and decay is not as rapid as would be expected if the debris were insulation, which typically has a large area-to-mass ratio.

"Breakup in Review: COBE," Nicholas Johnson, *Orbital Debris Monitor*, October 1993, pp. 16-18; interview, David S. F. Portree with Donald Kessler, November 25, 1997.

September JSASS forms committee on space debris prevention design standards at request of NASDA.

September 7 The Program Implementation Plan for the International Space Station (ISS), published on this date, declares that the "design and operation of the Space Station will provide a probability of no catastrophic failure from impact of 95 percent over a 10-year period. This performance is based on a corresponding requirement for a probability of no penetration of 90 percent over a 10-year period."

Orbital Debris Monitor, Vol. 6(4), October 1993.

October *Acta Astronautica*, the Journal of the IAA, publishes a "cosmic study" on orbital debris prepared by "an *ad hoc* expert group" of the IAA Committee on Safety, Rescue, and Quality. Its purpose is to

- "make clear how significant and severe the continued deposition of orbital debris into the near Earth environment is to the future use of space for all humankind"
- "provide some clear guidelines as to how the international community might wish to proceed in order to combat this growing space environmental hazard"
- "extend discussion of the debris issue by other international groups . . . to begin to formulate international agreements on this topic"

Members of the ad hoc group include Darren McKnight, Kaman Sciences, co-chair; Walter Flury, ESA/ESOC, co-chair; Vladimir Chobotov, The Aerospace Corporation; Nicholas Johnson, Kaman Sciences; Joseph Loftus, NASA JSC; Lubos Perek, Astronomical Institute CSAV; Dietrich Rex, TUBS; and A. A. Sukhanov, IKI. The study is adopted as a position paper of the IAA in 1995.

Acta Astronautica, Vol. 31, October 1993, pp. 169-191.

October 16-22 The 26th annual Space Safety and Rescue symposium is held in conjunction with the 44th International Astronautical Federation conference in Graz, Austria. Paper topics include a summary of the First European Conference on

Space Debris; the DISCOS European space debris database; progress on the NASA orbital debris safety standard ("the orbital debris handbook"); collision avoidance; orbital debris environment predictions; and the IAA orbital debris position paper. The IAA subcommittee on space debris meets for the first time.

Orbital Debris Monitor, Vol. 7(4), January 1, 1994; *Space Safety and Rescue 1993*, Gloria Heath, editor, AAS Science and Technology Series, Vol. 87, 1996.

October 18 The 1.8-ton Cosmos 1484 Meteor-Priroda remote-sensing satellite reached a 593-by-661-km sun-synchronous orbit at 98 deg of inclination on July 24, 1983. The satellite failed in February 1984 and decayed by this date to 549 by 596 km. On this date, at an altitude of 560 km over the Java Sea, the satellite undergoes highly energetic breakup. Orbital periods of debris pieces increase by up to 14 minutes. Within a month, U.S. Naval Space Command detects over 100 fragments, of which 15 are officially catalogued by mid-December. Following this detonation, Haystack data indicates a two-fold increase in 7-mm-to-1-cm debris between 450 km and 550 km.

Orbital Debris Monitor, Vol. 7(1), January 1, 1994; "Orbital Debris Damage," presentation materials, Eric Christiansen, May 10, 1996.

October 25-26 The 10th IADC meeting at TsNIIMash in Kaliningrad, Russia, produces Terms of Reference for governing IADC activities. The terms specify that IADC will consist of a steering group made up of representatives of each member plus the following working groups: Working Group 1 – Measurements; Working Group 2 - Environment and Database; Working Group 3 – Protection; and Working Group 4 – Mitigation. The IADC's structure is designed to foster coordinated international research into debris issues.

October 29 The Unit for Space Sciences of the University of Kent reports that the Olympus satellite might have been damaged when a Perseid meteoroid impact generated plasma around and within the spacecraft, producing short-circuiting in electronic components. ESA shut off Olympus on August 31 after depleting the spacecraft's fuel by lowering it 16 km below geosynchronous orbit.

The Olympus Satellite Anomaly: Hypervelocity Impact Effects and Meteoroid Collision Assessment, Unit for Space Sciences, University of Kent, October 29, 1993; "Olympus and the Perseids - An Encounter?" R. Douglas Caswell, Olympus Spacecraft Manager, presentation materials, NASA Leonid Meteor Shower Working Group Meeting, May 8-9, 1997.

November 8-12 The Third LDEF Post-Retrieval Symposium in Williamsburg, Virginia, includes 140 papers, of which 33 cover meteoroid and orbital debris effects on LDEF. The proceedings state that, while LDEF provided a "benchmark" for future space environmental effects studies, the symposium marks "the transition from focusing solely on a single spacecraft (LDEF) and its exposure to low Earth orbit, to focusing on a broad approach to study the space environment and its effects." For example, the symposium includes nine papers on preliminary analysis of the European Eureca satellite.

LDEF - 69 Months in Space, Third Post-Retrieval Symposium, NASA Conference Publication 3275, Parts 1 and 2, 1993.

November 17-23 The NRC's Committee on Space Debris holds its second meeting at the National Academies of Sciences and Engineering Beckman Center in Irvine, California. The Executive Committee session occurs November 17; report planning and writing sessions occur November 21-23. A workshop with briefings and plenary sessions takes place November 18-20. Representatives attend from NASA JSC, NASA Headquarters, ESA, NPO Energia, TUBS, the Embassy of India, the U.S. Air Force and U.S. Navy Space Commands, Canada's Department of Justice, Kaman Sciences, China Great Wall Industries, Inc., the U.S. Air Force Phillips Laboratory, Japan's National Aerospace Laboratory, and other international industrial, government, and research organizations.

Interview, David S. F. Portree with Donald Kessler, November 25, 1997; *Briefing Book: Committee on Space Debris Workshop*, November 18-23, 1993.

December 1 The German FGAN radar observes the Cosmos 1484 spacecraft, which underwent an energetic debris-producing event on October 18, but provides few new clues to the breakup's cause. Results indicate that the spacecraft is spinning every 70 seconds but remains largely intact. The USSPACECOM database contains no conjunctions, so collision with a tracked space object is not a likely breakup cause. The spacecraft contained three stored energy sources – four small tanks covered by 40 to 50 layers of foil insulation rated to 120 atmospheres burst pressure but only pressurized to one atmosphere; bus pressurized at 0.6 atmospheres; and Ni-Cad batteries in thin aluminum cases.

Orbital Debris Monitor, Vol. 7(1), January 1, 1994.

December 2-13 During STS-61, the first HST servicing mission, the Cosmos 1441 satellite conjuncts three times with Space Shuttle Endeavour. On December 5, EVA astronaut Kathy Thornton manually jettisons the damaged 160-kg starboard solar array, which could not be rolled shut as planned for return to Earth. The partially closed array remains in orbit at a high altitude despite early reports that it would reenter quickly. The Wide Field and Planetary Camera, port solar array, and other HST parts are returned to Earth for meteoroid / orbital debris analysis.

Memorandum with attachments, Steven Stich, DM32/Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997; *Walking to Olympus: An EVA Chronology*, David S. F. Portree and Robert C. Trevino, Monographs in Aerospace History #7, NASA Headquarters, October 1997, p. 102.

1994		
	End of year launches reaching Earth orbit or beyond (since 1957)	3663
	End of year satellites (objects in orbit)	7774

January 25 The Clementine spacecraft, also known as Deep Space Program Science Experiment 1, launches on a U.S. Air Force Titan II missile modified to serve as a space launcher. Clementine, the first in a planned series of technology demonstration missions jointly sponsored by the Ballistic Missile Defense Organization and NASA, is the first U.S. lunar explorer since 1972. The residual propellant vent on the Titan II's 3300-kg upper stage is locked shut because stage instability caused by venting had contributed to the failure of a

NOAA Landsat spacecraft in October and there was insufficient time to repair the problem before Clementine's scheduled launch. About 196 kg of oxidizer and 26 kg of fuel are left on board. On February 7, the stage ruptures 245 km over the South Atlantic, creating several hundred debris pieces. After some initial concern, the breakup is determined to pose little threat to STS-60, in orbit at this time. The breakup has only a short-lived effect on the debris environment and none of the fragments are catalogued. The Titan II's interstage adapter is left in a 259-km-by-296-km orbit at 67.2 deg of inclination. It carries the Orbital Meteoroid and Debris Counter, a 0.5-kg, $200,000 experiment that operates until the adapter reenters in May 1994.

Orbital Debris: A Technical Assessment, National Research Council, 1995, p. 48; *Orbital Debris Monitor*, Vol. 7(2) April 1, 1994.

February 3-11

On STS-60 Sergei Krikalev becomes the first Russian cosmonaut to launch aboard a U.S. spacecraft. The mission is also the first successful ODERACS flight. On February 9, Discovery's crew successfully deploys six ODERACS spheres. One two-inch sphere is polished stainless steel; the second is sand-blasted stainless steel. One four-inch and one six-inch sphere are sand-blasted aluminum, and one four-inch and one six-inch sphere are chrome-plated aluminum. The Haystack radar collects data in April and June 1994 to calibrate its principal polarization channel. The ODERACS spheres reenter between October 2, 1994 and March 3, 1995. Results of this and the second successful ODERACS flight experiment (February 1995) yield improvements in orbital debris tracking software and calibration techniques.

"Low Earth Orbit Debris History 1990-1994," Thomas J. Settecerri and Eugene Stansbery, *Space Forum*, Vol. 1, No. 1-4, 1996, pp. 63-82; *Radar and Optical Ground Measurements Final Report - Orbital Debris Radar Calibration Spheres* (JSC 27241), G. H. Cress, *et al*, June 1996.

February 8

The transtage of the Titan rocket that launched the IDCSP 3-1 satellite on July 1, 1967, undergoes an energetic event that produces a change in its orbital period. No fragments are detected, but the event probably generated small debris.

Orbital Debris Monitor, Vol. 9(1), January 1, 1996; "Debris in Geosynchronous Orbits," Antonio F. Pensa, G. Edward Powell, Eugene W. Rorik, and Ramaswamy Sridharan, *Space Forum*, Vol. 1, No. 1-4, 1996; special issue - proceedings of the 1st International Workshop on Space Debris, October 1995, pp. 23-37.

February-March

The topic of space debris appears on the agenda of U.N. COPUOS S & T Subcommittee as a separate item for first time, largely through the efforts of the IADC countries. NASA Orbital Debris Program manager George Levin formally moved to place the item on the agenda. According to Dietrich Rex, who became Chairman of the S & T Subcommittee in 1996, "all delegations welcomed the new agenda item and emphasized its importance." The U.S. and Russia had vetoed including orbital debris on the S & T Subcommittee agenda as a formal item up to this point because both wanted to gather additional data to permit informed decisions on orbital debris policy and avoid potentially uninformed inputs from and decisions by non-spacefaring nations. The late 1980s and early 1990s saw a "satellite proliferation," however, so the topic was placed on the S & T Subcommittee agenda as part of orbital debris educational efforts.

“The Role of the Scientific & Technical Subcommittee of UN-COPUOS for the Space Debris Work of the United Nations,” Dietrich Rex; interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997.

March The HAX radar begins collecting orbital debris data. HAX was developed from surplus communication antennas and uses the Haystack control and data systems. The radar, which became operational in 1993, collects 371 hours of data in FY 1994. HAX, which stares at zenith, is less sensitive than Haystack, but has a wider of field of view so can collect more data.

Measurements of the Orbital Debris Environment: Comparison of the Haystack and HAX Radars, JSC-27971, T. J. Settecerri and E. G. Stansbery, August 1997; *Haystack Radar Measurements of the Orbital Debris Environment: 1994-1996*, JSC-27842, T. J. Settecerri, E. G. Stansbery, J. N. Opiela, and R. Henderson, May 1997.

March-September The British National Space Center (BNSC), DARA, CNES, and Italy’s Agenzia Spaziale Italiana (ASI) hold a series of meetings with ESA to identify national facilities of use in orbital debris research and to develop a common European policy on orbital debris mitigation.

March 10 The Small Expendable Deployer System (SEDS)-2 was launched on March 5 attached to the upper stage of a Delta II. Upon arriving in 327-km-by-331-km orbit at 32.3 deg inclination, SEDS-2 pays out a 20-km-long, 0.75-mm-diameter tether with a 25-kg end weight / payload. At the tether’s full length of 20 km, it has a cross-section area of 15 sq m and a surface area of 47 sq m. On this date the tether breaks, leaving the SEDS-2 deployment system and upper stage trailing a 7-km tether with a total area large enough to be seen by the naked eye from the Earth’s surface. Kwajalein Atoll’s 1.5-m telescope photographs the tether on March 19. An orbital debris collision with the tether is proposed as a cause for the break; another theory is that the tether was weakened by interaction with atomic oxygen, though the break might have happened too soon after launch for atomic oxygen to have been a significant factor. Donald Kessler first noted the vulnerability of tethers to orbital debris and meteoroids in 1984, when he predicted that a 20-km aluminum tether 1 mm across will be cut by an impact within an average of 3 weeks. The SEDS-2 tether and upper stage decay rapidly because they have a large area-to-mass ratio, and reenter on May 8, 1994.

Interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997; interview, David S. F. Portree with Donald Kessler, November 25, 1997; “Tether Sever Rate from Meteoroids and Debris,” memorandum, Donald Kessler to Jim McCoy, August 20, 1984; *Orbital Debris: A Technical Assessment*, National Research Council, 1995, p. 97.

March 21 An ISS Analysis Integration Team meeting on this date is the setting for a disagreement between Russia and the U.S. over the ISS orbital debris environment model. The Russian Space Agency expresses a desire to apply its own, less stringent requirements to its modules, but is convinced to use the 1991 NASA model after Donald Kessler briefs Russian ISS manager Vladimir Solovyov on the methods and data used to derive it. Russian requirements were based on experience with the Salyut 6, Salyut 7, and Mir stations, which presented less cross-sectional area than ISS. In addition, past Soviet stations have operated at altitudes lower than ISS; so low, in fact, that debris tends to be nearing reentry and thus does not persist in posing a threat to the station.

Interview, David S. F. Portree with Donald Kessler, November 25, 1997; interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997.

April 9-20

During the STS-59 / Space Radar Laboratory-1 mission, mission requirements dictate that Space Shuttle Endeavour's attitude not be controlled to avoid orbital debris impacts on its windows. Endeavour encounters a paint chip, suffering a window ding 1.2 cm across. The window is replaced upon return to Earth.

"Orbital Debris Damage," presentation materials, Eric Christiansen, May 10, 1996.

May 12-14

Japen hosts the 11th IADC meeting at Tsukuba Space Center. The meeting's sixty-five participants hear opening remarks by Susumu Toda, National Aerospace Laboratory. NASA Orbital Debris Program manager George Levin presents photographs of the frayed Tethered Satellite System-1 Reflight (TSS-1R) tether, believed by many to have been cut by a meteoroid or orbital debris impact. ESA's Walter Flury reveals that Eureca postflight analysis found a 6-mm impact pit. Russia is not fully represented at this IADC. On May 12, Working Groups 1, 2, and 4 meet in a joint session chaired by Andrew Potter, NASA JSC, to discuss "topics of common interest." These include international cooperation on GEO observations; an international database of spacecraft failures and anomalies; HST solar array impact study results; reports on the ODERACS and Pion radar calibration experiments; correlation of the SSN and Russian SSS catalogs; the status of ESA 1-m Zeiss orbital debris telescope; and other topics. Working Groups 1, 2, and 3 meet jointly on May 13 to discuss NASDA hypervelocity impact testing; breakup of the Clementine Titan II upper stage; the NASDA GEO reorbit policy; ITU reorbit requirements; orbital debris issues associated with geosynchronous transfer orbits; and other topics.

"Min. of the 11th IADC Mtg., May 12-14, 1994," memorandum with attachments, Susumu Toda to Distribution.

June 14

An industrial consortium led by Unispace Kent of Britain, and consisting of Space Applications Services of Belgium, Mare Crisium of Britain, ONERA / DERTS of France, and the C. Maag Company of the U.S. presents the Final Presentation of the Eureca impact study begun in July 1993. An interim report issued in March stated that Eureca surfaces reveal eight times more damage than expected from meteoroid and / or orbital debris. The consortium reports that no functional failures on Eureca were caused by impact; the front of the solar arrays suffered 30 percent (about 1000) of the total impacts, indicating impactor direction of origin; and the largest crater found measures 6.4 mm across.

Orbital Debris Monitor, Vol. 7(4), October 1, 1994.

June 26-27

As part of the 30th Joint Propulsion Conference in Indianapolis, Indiana, a Solid Rocket Motor (SRM) aluminum slag production workshop is held. In their report, workshop participants write that SRMs burning aluminum perchlorate propellant produce aluminum oxide and small amounts of unburned aluminum metal as by-products. Liquid metal forms a ring around the recessed base inside the SRM nozzle until no more can fit, then breaks loose, leaves the nozzle, and contributes aluminum slag fragments to the orbital debris environment.

> *Workshop Report: Modeling of Slag Generation in Solid Rocket Motors*, M. Salita, 30th Joint Propulsion Conference, Indianapolis, Indiana.

July 14 The "Scientific Meeting on Space Debris" at COSPAR XXX in Hamburg, Germany, is the first orbital debris meeting sponsored by both COSPAR and the IAA. The meeting consists of two sessions – "measurements and modelization of space debris and meteoroids" (chair, Eugene Stansbery, NASA JSC; referee H. Klinkrad, ESA / ESOC), and "modelization and protective measures for the particulate environment" (chair, J.A.M. McDonnell; referee Robert Reynolds, Lockheed) – and includes eight invited papers, 13 contributed papers, and four posters.

> *Advances in Space Research, Space Debris*, Walter Flury, editor, Vol. 16, Number 11, 1995.

August Last in a series of five GEO debris observing runs performed at Mt. Haleakala, Maui, Hawaii, by David Talent, Andrew Potter, and Karl Henize (until his death in 1993). The series, which began in December 1992, accumulated 13,516 CCD images in 252 hours over 42 nights. At least one object appeared in 26.7 percent of the 6758 fields observed. Of these, 208 objects did not correlate with any known satellite.

> David Talent, Andrew Potter, and Karl Henize, "A Search for Orbital Debris in GEO," *Proceedings of the Second European Conference on Space Debris*, ESA SP-393, May 1997, pp. 99-104.

August At its 66th conference in Buenos Aires, Argentina, the International Law Association adopts a draft *International Instrument on the Protection of the Environment from Damage Caused by Space Debris* (the "Buenos Aires Instrument"), which was drafted by its Space Law Committee. The convention contains no technical means to mitigate debris creation, nor does it amount to policy or law. The association commenced study of orbital debris legal issues in 1986.

> *Space Policy*, February 1996, pp. 82-84; *Orbital Debris: A Technical Assessment*, National Research Council, 1995, p. 187.

September NASA orbital debris scientists discuss with a Russian representative to the IADC the possibility that sodium potassium (NaK) liquid metal coolant escaping from Bouk reactors in Russian RORSAT satellites is the source of 1-cm debris observed by the Haystack, Goldstone, and Arecibo radars between 850 and 1000 km and at about 725 km. The Russian representative reports after discussions with the RORSAT Chief Designer that RORSATs contain no small particle sources, and suggests that the radars are detecting uranium fuel rod fragments. On October 4, the RORSAT Deputy Chief General Designer confirms that NaK serves as RORSAT coolant, and that NaK droplets can be released when the fuel rods are ejected after reboost to neutralize the RORSAT reactor.

> *The Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites*, D. J. Kessler,

M. J. Matney, R. C. Reynolds, R. P. Bernhard, E. G. Stansbery, N. L. Johnson, A. E. Potter, D. Anz-Meador, JSC-27737, NASA JSC, February 21, 1997; interview, David S. F. Portree with Donald Kessler, November 25, 1997.

September 21-23 The First European Space Debris Course at the University of Kent, United Kingdom is sponsored by Century Dynamics, the Defense Research Agency of the United Kingdom, ESA, Kaman Sciences Corporation, Matra Marconi, Space Guard of Australia, TUBS, the University of Kent, and the University of Utrecht.

Orbital Debris Monitor, Vol. 7(4), October 1, 1994.

October 9-14 Orbital debris papers dominate the 27th annual Space Safety and Rescue symposium of the IAA held in conjunction with the 45th International Astronautical Federation meeting in Jerusalem, Israel. Topics include CNES debris modeling activities; fragmentation of Russian upper stages in LEO; orbital debris minimization design; ESA's Meteoroid and Space debris Terrestrial Environment Reference (MASTER) debris model; and efforts to reduce debris produced by the Zenit rocket. A special session, including three papers, focuses on orbital debris and satellite constellations. The IADC Steering Group, meeting in conjunction with the IAF, agrees to invite China to join the IADC. The China National Space Administration officially accepts IADC membership in July 1995.

Space Safety and Research 1994, Gloria Heath, editor, AAS Science and Technology Series, Vol. 88, 1996.

November Donald Kessler proposes an orbital debris environment "Intermediate Model" which lowers overall debris flux by a factor of 2, but shows that simple, meaningful environment models are no longer possible.

Interview, David S. F. Portree with Donald Kessler, November 25, 1997.

November 3-14 During the STS-66 ATLAS 3 atmospheric science mission, orbiter Atlantis conjuncts twice with ODERACS spheres within the 5-km-by-25-km-by-5-km alert box.

Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997.

December 13-14 The FGAN (Germany) and Fylingdales (United Kingdom) radars and Royal Greenwich Observatory (United Kingdom) and Zimmerwald (Switzerland) optical systems conduct a 24-hour LEO debris measurement campaign.

1995

End of year launches reaching Earth orbit or beyond (since 1957)	3738*
End of year satellites (objects in orbit)	7868

*Fewer launches took place this year than in any since 1963.

January-February Kaman Sciences and the Center for Program Studies, Russian Academy of Sciences work together under contract to NASA JSC to refine and expand a list of Soviet / Russian satellites known or suspected to have broken up in Earth orbit. The two main objectives of the study are to

- identify Russian / Soviet breakups unknown in the West

- collect data for improved modeling of the near-Earth space environment

A U.S. list of breakups provided by Kaman in October 1994 was supplemented in December by a preliminary Russian list of 131 satellite breakups. This is subsequently expanded to include 142 breakups, two of which are not considered breakups by the U.S. After discussions to resolve discrepancies, Kaman consolidates the lists and analyzes breakup causes. The company finds that the most common cause (48 breakups) is deliberate self-destruction. While Soviet / Russian satellites are involved in about two-thirds of all known breakups, fragments from these satellites account for only 17 percent of the catalogued Earth satellite population still in orbit. The database becomes the basis for the common debris event list maintained by IADC Working Group 4.

> "History of Soviet/Russian Satellite Fragmentations - a Joint U.S.-Russian Investigation," Nicholas Johnson, Grigoriy Chernyavskiy, and Nikolai Morozov, *Space Forum*, Vol. 1, No. 1-4, 1996, pp. 95-102.

February 3-11

The STS-63 astronauts deploy ODERACS II spheres and dipoles from Discovery's payload bay on February 5 to calibrate ground-based orbital debris radars. The three spheres measure two, four, and six in across, respectively. Two of the dipoles measure 5.255 in long by 0.040 in wide, while a third measures 1.740 in by 0.040 in. This experiment and the first successful ODERACS experiment (February 1994) yield improvements in orbital debris calibration techniques and tracking software. The ODERACS II spheres and dipoles decay from orbit between February 27, 1995, and September 29, 1996. On February 6, Discovery performs a fly-around of the Mir space station, during which the orbiter crew performs Development Test Objective (DTO) 1118, a photographic survey of the station's exterior using hand-held 35-mm Nikon and 70-mm Hasselblad cameras, which reveals features as small as 2 or 3 mm across. The payload bay cameras suffice for larger features. DTO 1118 is designed as an ISS risk mitigation activity with objectives that include

- providing NASA engineers with assurance of crew and orbiter safety while in Mir's vicinity

- assess Mir's overall condition

- study the effects of the space environment on a long-duration space vehicle

- understand the impact of attitude control jet plume impingement during proximity operations

The astronauts snap 655 35-mm photographs and 355 70-mm photographs.

> "Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson,

Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, July 27- Aug 1, 1997, San Diego, California*; Radar and Optical Ground Measurements Final Report - Orbital Debris Radar Calibration Spheres* (JSC 27241), G. H. Cress, *et al*, June 1996.

February 6-17

The Scientific & Technical Subcommittee of U.N. COPUOS holds its 32nd session. Walter Flury of ESA makes available to the subcommittee the IAA position paper on orbital debris. The subcommittee adopts a multi-year work plan with a different focus assigned to each year.

1996: Orbital debris environment measurement

1997: Modeling the orbital debris environment and risk assessment

1998: Orbital debris mitigation

1999: Aggregation of data

According to the multi-year plan, after 1999 discussions may commence on a U.N. plan of action for dealing with orbital debris, assuming that consensus is achieved.

"The Role of the Scientific & Technical Subcommittee of UN-COPUOS for the Space Debris Work of the United Nations," Dietrich Rex; interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997.

February 9

The ITU releases regulatory standard ITU-R S.1003, "Environmental Protection of the Geosynchronous Orbit." The Standard declares, among other things, that GEO satellites should reorbit to an altitude 300 km above GEO plus 1000 times the area-to-mass ratio.

ITU-R S.1003, "Environmental Protection of the Geosynchronous Orbit," February 9, 1995.

Early March

Los Alamos National Laboratory determines that NaK escaped from RORSATs is the probable source of increased 1-cm orbital debris at altitudes between 850 km and 1000 km and at about 725 km. The laboratory determines that micrometeoroid penetrations of radiator surfaces is probably not the cause of leaks allowing the NaK to escape. A total of 15 Bouk RORSAT reactors have been boosted to graveyard orbit since Cosmos 1176 in 1980, each with the potential for spilling five liters of NaK from its cooling loop. This would place 70 kg of NaK droplets between 850 km and 1000 km and five kg at 725 km, quantities in accordance with Haystack and Goldstone radar data.

The Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites, D. J. Kessler, M. J. Matney, R. C. Reynolds, R. P. Bernhard, E. G. Stansbery, N. L. Johnson, A. E. Potter, D. Anz-Meador, JSC-27737, NASA JSC, February 21, 1997; interview, David S. F. Portree with Donald Kessler, November 25, 1997.

March 2-18

On STS-67, orbiter Endeavour carries the ASTRO 2 ultraviolet astronomy payload. The Japanese Space Flyer Unit (SFU) was scheduled to launch on March 15 on an H-2 rocket into an orbit similar to Endeavour's, creating a potential Collision on-orbit Avoidance (COLA) issue. Because of technical problems, NASDA postpones the launch until March 18. The orbiter is planned to return to Earth on March 17, but is waved off for 24 hours. Talks between Japanese and U.S. mission operations officials resolve the renewed COLA issue. NASDA agrees to launch SFU no earlier than 6 minutes into its launch window to prevent the spacecraft and its streamlined payload fairing from approaching Endeavour any closer than 200 km. SFU is launched into a Shuttle-type orbit because it is scheduled to be retrieved by Endeavour early in 1996.

Interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997; e-mail from Donald Pearson, NASA JSC Mission Operations Directorate, March 2, 1998.

March 8-10

The IADC holds its 12th meeting in Houston. China participates as an observer. Working Group 1 (Measurements - A. Potter, chair) includes presentations on discrepancies between data sets collected by the U.S. Haystack and German FGAN radars and results of examination of HST and Eureca returned surfaces. Working Group 2 (Modeling - S. Veniaminov, chair) includes presentations on the NASA EVOLVE and ESA CHAIN and MASTER models; exchange of U.S. and Russian satellite catalogues; and the RORSAT NaK issue. Working Group 3 (Protection - H. Heusmann, chair) includes presentations on the Shuttle and debris while Working Group 4 (Mitigation - J. Loftus, chair) includes presentations on NASA's orbital debris safety standard, Ariane 5 debris issues, debris removal using lasers, and geosynchronous transfer orbit lifetimes. The U.S. delegation presents its RORSAT findings with a request that Russia assist in understanding NaK debris. The Russian delegation insists that RORSAT NaK is not required to explain Haystack and Goldstone data.

The Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites, D. J. Kessler, M. J. Matney, R. C. Reynolds, R. P. Bernhard, E. G. Stansbery, N. L. Johnson, A. E. Potter, D. Anz-Meador, JSC-27737, NASA JSC, February 21, 1997; "Comparison of Space Debris Models with Haystack Radar Measurements," A. Nazarenko, *12th Inter-Agency Space Debris Coordination Meeting Proceedings*, Vol. II, Presentations; interview, David S. F. Portree with Donald Kessler, November 25, 1997.

June 14

The NRC publishes *Orbital Debris - A Technical Assessment*. The report is designed to be the basis for a multi-year research program independent of the ISS and Shuttle program debris assessments. In addition it is to provide an overview of debris issues and to provide guidance for "a responsible approach to orbital debris," which will require

- "continuing measurement and modeling efforts to increase our knowledge of the current and future debris population"
- "the development of tools to aid spacecraft designers in protecting their spacecraft appropriately against the existing debris hazard"
- "widespread implementation of appropriate measures to minimize the creation of additional debris"

The report states that "[t]he threat that orbital debris poses to international space activities is presently not large, but it may be on the verge of becoming significant. If and when it does, the consequences could be very costly - and extremely difficult to reverse. By contrast, the cost of reducing the growth of the hazard can be relatively low. . ." Specific recommendations include:

- increase understanding of the GEO debris environment.

- develop a strategy for obtaining data on the sources and evolution of the small debris population and use this data to compile a standard population characterization reference model

- develop new techniques for hypervelocity impact testing at LEO collision speeds and analytical tools consistent over a range of debris impact shapes, velocities, and compositions

- write a handbook describing the capabilities of international hypervelocity facilities

- study impact damage effects on critical spacecraft components

- write and distribute widely a debris mitigation guide for spacecraft designers

The NRC calls on spacecraft designers to

- "adopt design requirements to dissipate on-board energy sources to ensure that spacecraft or rocket bodies do not explode after their functional lifetimes"

- avoid "release of mission-related objects during spacecraft deployment and operations [and] intentional breakups. . .whenever possible. . .no intentional breakups expected to produce numerous debris with orbital lifetimes longer than a few years should be conducted in Earth orbit"

- design "spacecraft and rocket bodies. . .to minimize the unintentional release of surface materials, including paint and other thermal control materials, both during and after their operational lifetimes"

- remove from LEO or reduce the lifetime of spacecraft and rocket bodies in LEO and highly elliptical orbits passing through LEO at the end of their functional lifetime

- "Until [further studies of GEO disposal orbits] produce a verifiably superior long-term strategy for dealing with the GEO debris hazard, "[satellite] operators. . . should. . .reorbit their spacecraft at the end of their functional lifetimes if they are capable of safely performing a reorbiting maneuver to a disposal orbit at least 300 km from GEO."

Orbital Debris: A Technical Assessment, National Research Council, 1995, pp. 3-9, 14; interview, David S. F. Portree with Nicholas Johnson, November 6, 1997.

June 29-July 4

STS-71 is the first Shuttle-Mir (ISS Phase 1) docking mission. Atlantis is docked to Kristall from June 27 to July 7, 1995, which is in turn docked to Mir's forward (-X) docking port. This is also the second DTO 1118 flight. The astronauts survey Mir's exterior using the same types of cameras used on STS-63, plus an electronic still camera capable of imaging larger impact features. The crew takes 215 35-mm and 435 70-mm photos. A small orbital debris object associated with the Progress-M 27 automated cargo ship conjuncts with Atlantis and Mir within the 5-km-by-25-km-by-5-km alert box 17 times in one 13-hour period. Six of these conjunctions occur within the 2-km-by-5-km-by-2-km maneuver box. USSPACECOM sensors have difficulty distinguishing the object from the nearby orbiter and Mir station, leading to dramatic changes in its listed state vector. Atlantis suffers a window impact – possibly a piece of aluminum slag from an SRM – creating a 2-mm pit.

Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997; "Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson, Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, July 27-Aug 1, 1997, San Diego, California; *Orbital Debris Quarterly News*, Vol. 2, Issue 2, April-June 1997.

July

ESA publishes the final report on its MASTER model. MASTER is written by the IfRR at TUBS. H. Klinkrad is ESA / ESOC technical supervisor; IfRR TUBS head is Dietrich Rex; and MASTER report author is Holger Sdunnus.

MASTER Final Report, ESOC Contract 10453/93/D/CS, July 1995.

August

NASA releases *Guidelines and Assessment Procedures for Limiting Orbital Debris* (NASA Safety Standard 1740.14), a "companion" to NMI 1700.8 (April 5, 1993) which "provides specific guidelines and methods to comply with the NASA policy to limit orbital debris generation." The standard, drafted by Joseph Loftus, NASA JSC, and Robert Reynolds, Lockheed, is designed to "be used by the program manager or project manager as the primary reference for conducting debris assessments."

Guidelines and Assessment Procedures for Limiting Orbital Debris, NSS 1740.14, August 1995.

September 28

Space Shuttle Meteoroid and Orbital Debris Damage Assessment Team is chartered at the request of Shuttle Program manager Tommy Holloway following a letter from Joseph Loftus pointing out possible orbital debris consequences for the Shuttle and ISS programs. The Shuttle was designed in the early 1970s for a meteoroid environment, not a mid-1990s orbital debris environment. The team, chaired by William Schneider, NASA JSC, consists of NASA JSC, NASA MSFC, and Rockwell International (Shuttle prime contractor) representatives. According to Holloway's letter establishing the team, its major objectives are to

- "review the environmental modeling and assess accuracy and recommend improvement as appropriate"

- “review orbiter modeling used in predicting orbiter damage and assess accuracy and recommend improvement as appropriate”

- “[a]ssess the potential for damage to the orbiter during operations planned for: a) Shuttle-Mir; b) International Space Station; and c) Science Missions”

- “[r]ecommend concepts and methods to reduce risk to critical orbiter areas”

- “[r]eview the reporting process and make recommendations for improvements”

> “Space Shuttle Meteoroid and Debris Damage Team,” memorandum to distribution, MA/Manager, Space Shuttle Program, to Distribution, September 28, 1995.

October The Earth Space Institute and ASCONT organizations in Russia sponsor the 1st International Workshop on Space Debris in Moscow, which includes sessions on “Remote and *In-Situ* Debris Observations,” “Identification of Debris Sources,” “Critical Review of Debris Modeling,” “Debris Mitigation,” “Debris Mitigation Measures of Constellations,” and “Debris Countermeasures Effectiveness.” Participants from Russia, the U.S., Japan, and Europe present more than two dozen papers.

> *Space Forum*, Volume 1, No. 1-4, 1996; special issue - proceedings of the 1st International Workshop on Space Debris, October 1995.

October 1 *Orbital Debris Monitor* publishes a report by Andrei Nazarenko, Russian Academy of Sciences, on Russian efforts to model the small orbital debris environment. He states that NaK from RORSAT Bouk reactors need not be invoked to explain the preponderance of 1-cm debris found in Haystack data, concluding

> that the altitude range of 800-to-1000-km is now the most “populated” with large catalogued objects. It comprises presently about 1800 objects larger than 10-to-20-cm in size. The total yearly average number of their collisions with small particles sizing greater than 0.3 cm is some tens. One cannot exclude that it is just these collisions which give rise to an increased number of small particles in the above-mentioned altitude range, which have been recorded by Haystack Radar.

> *Orbital Debris Monitor*, Vol. 8(4), October 1, 1995.

October 2-6 The 28th annual Space Safety and Rescue symposium is held in conjunction with the 46th International Astronautical Federation meeting in Oslo, Norway. Paper topics in the plenary session on orbital debris include U.N. principles on nuclear power sources in space; an update on NASDA orbital debris mitigation standards; NASDA efforts to minimize the number of upper stages left in geosynchronous transfer orbit; IADC activities; new findings on collisional cascading; modeling the orbital debris environment; and the U.S. space nuclear program. The IADC Steering Group, which meets during the meeting, agrees to accept applications for membership from CNES, BNSC, and Indian Space Research Organization (ISRO), bringing the total number of IADC members to eight. The Steering Group then amends the IADC Terms of Reference to stipulate that IADC members must participate in at least the Steering Group and Working Group 4 (Mitigation) to remain eligible for membership – this move is designed to ensure that the IADC will not include inactive partners. In addition, the Steering Group decides that members may include in their delegations representatives from agencies other than the member's national space agency, including representatives from industry.

October 20

ESA astronaut Thomas Reiter and Russian cosmonaut Sergei Avdeyev perform a 5-hour, 11-minute EVA to install the European Space Exposure Facility (ESEF) 1 on the exterior of Mir's Spektr module. Reiter installs two cassettes designed to be exposed by remote control from within Mir. Four of five experiments aim to detect, measure, and / or collect meteoroid and orbital debris particles.

Walking to Olympus: An EVA Chronology, David S. F. Portree and Robert C. Trevino, Monographs in Aerospace History #7, NASA Headquarters, October 1997, p. 115; "The European Space Exposure Facility (ESEF)," Sunil Deshpande, *Orbital Debris Monitor*, pp. 11-14.

October 20-November 5

On STS-73 orbiter Columbia orbits Earth for 16 days carrying the United States Microgravity Laboratory (USML) 2 Spacelab mission. Mission requirements prepared by NASA MSFC pointed Columbia's payload bay in the direction of motion (the "ram" direction); however, in a letter Joseph Loftus warned Shuttle Program Manager Tommy Holloway against this attitude, so the oldest orbiter points its port wing in the ram direction for about 13 days of the mission. The port payload bay door is held partially closed to shield Columbia's Extended Duration Orbiter cryogenics pallet and the USML-2 Spacelab Long Module from impact. The largest of many impact craters detected on Columbia after landing is located on the port payload bay door. The crater, 17 mm in diameter and 6 mm deep, yields a 1.2-mm circuit board fragment. Three of Columbia's windows are replaced - one for orbital debris damage, one for meteoroid damage, one for damage caused by an impactor of indeterminate origin.

Orbital Debris Monitor, Vol. 9(1), January 1, 1996; interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997; "Orbital Debris as Detected on Exposed Spacecraft," R. Berhard and E. Christiansen, *Orbital Debris Quarterly News*, Vol. 2, Issue 4, October-December 1997.

November 4

Radarsat is a joint Canadian / U.S. Synthetic Aperture Radar satellite launched on a U.S. Delta II rocket. NASA and NOAA participate in Radarsat, which is intended to operate until 1999. On this date the 3000-kg satellite reaches its intended 791-km-by-793-km sun-synchronous orbit at 98.6 deg of inclination. Radarsat has a 5-sq-m cross-section and orbits at an altitude known for its relatively high orbital debris flux, so the Canadian Space Agency called upon NASA JSC to assess the orbital debris risk to Radarsat and help develop protection. Radarsat's vulnerabilities were assessed in the HIT-F, then its multi-layer insulation blankets, radiators, and component walls were reinforced as necessary. Increasing Radarsat's survivability from 0.5 to 0.87 added only 17 kg to Radarsat's mass.

"Effects of Space Debris on Commercial Spacecraft - The RADARSAT Example," H. R. Warren and M. J. Yelle, *Preservation of Near-Earth Space for Future Generations*, John A. Simpson, editor, 1994, pp. 77-83.

November 12-20 On mission STS-74 orbiter Atlantis delivers the Docking Module to Mir's Kristall module, which was docked to Mir's -Z lateral port. The orbiter remains docked to Mir from November 15 to November 18, 1995. During this period, the crew performs DTO 1118 photography, snapping 470 35-mm and 560 70-mm images of Mir's exterior. Two objects (Mir debris and a Chinese CZ-3 rocket body) conjunct with Atlantis within the 5-km-by-25-km-by-5-km alert box.

"Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson, Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, July 27-Aug 1, 1997, San Diego, Canada; Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997.

December 10 Cosmos 398 is a museum piece – an unpiloted test version of the Soviet LK piloted moon lander. It was launched on a Soyuz rocket on February 26, 1971. Another LK, Cosmos 434, reentered in 1981. On this date the Cosmos 398 reenters Earth's atmosphere near the Falkland Islands in the South Atlantic Ocean. For the first time data on the uncontrolled reentry of a space object is shared among the U.S., Europe, and Russia in near real-time. The U.S. and Russia share tracking data, while Europe shares analysis of that data but does not track Cosmos 398.

Interview, David S. F. Portree with Nicholas Johnson, December 15, 1997;

1996

End of year launches reaching Earth orbit or beyond (since 1957)	3811
End of year satellites (objects in orbit)	8517

January 11-29 During STS-72, a 1-mm aluminum particle impacts on the inside of Endeavour's open rudder speed brake, perforating the orbiter's aluminum honeycomb tail structure. Endeavour maneuvers to avoid the Miniature Seeker Technology Integration 2 (MSTI-2) satellite before it conjuncts with the orbiter within the 2-km-by-5-km-by-2-km maneuver box. Endeavour recovers the SFU satellite and returns it to Earth, where it is subjected to orbital debris analysis by the JSASS Study Group on Space Debris and Micrometeoroid Impact Detection.

Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997.

February 8 Thomas Reiter and Yuri Gidzenko perform an EVA to retrieve the ESEF 1 orbital debris and meteoroid collectors installed outside Mir's Spektr module in October. The ESEF 1 collectors return to Earth with Reiter on February 29.

1996

Walking to Olympus: An EVA Chronology, David S. F. Portree and Robert C. Trevino, Monographs in Aerospace History #7, NASA Headquarters, October 1997, pp. 117-118.

February 11-23

The 33rd session of the U.N. COPUOS S & T Subcommittee discusses orbital debris measurement. TUBS Professor Dietrich Rex is elected subcommittee chair. The subcommittee invites the IADC to present a paper on orbital debris at its 1997 meeting. Papers on orbital debris measurements are presented, and the participants draft the first part of a planned U.N. report on orbital debris.

"Discussions in the United Nations in 1996," Lubos Perek, IISL-96-IISL-4.08, 1996; "The Role of the Scientific & Technical Subcommittee of UN-COPUOS for the Space Debris Work of the United Nations," Dietrich Rex.

February 19

The Russian Proton Block DM used to boost the Raduga 33 satellite to GEO explodes near its first geosynchronous transfer orbit apogee soon after launch, producing at least 200 orbital debris objects. None are catalogued.

Orbital Debris Quarterly News, Vol. 2, Issue 1, January-March 1997.

February 22-March 9

During the 16-day STS-75 mission, an orbital debris object creates a 1-mm crater in TSS-1R hardware in Columbia's payload bay, forming a secondary ejecta stain and a 5-mm spall on the impact's rear face. Upon return to Earth one of Columbia's windows is replaced for orbital debris damage. The large impacts that occurred on missions STS-73, STS-72, and STS-75 probably reflect more in-depth studies of orbiter surfaces and a time-variable debris environment, not a persistently elevated debris flux posing a new threat to orbiters. However, the effects of the impacts are long-lasting because they help raise awareness of the relative vulnerability of the orbiter to impacts, lending credence to efforts to reinforce orbiter radiators and wing leading edges. The TSS-1R tether snaps near full 20-km extension on February 25. Meteoroid or orbital debris impact are absolved as the cause despite early speculation; the review board determines that the most probable cause was damage to the tether caused by incorrect tolerance dimensions in support structure. The TSS-1R satellite reenters on March 19.

"TSS-1R: The Mission," *Spaceflight Environment,* Vol. VII, No. 2, July 1996, pp. 5-9

February 28-March 1

The IADC holds its 13th meeting at ESA / ESOC in Darmstadt, Germany. The organization prepares a draft Common Database Cooperative Agreement and draft IADC Recommendation for Space Debris Management. The CNES, BNSC, and ISRO join the IADC. New Working Group chairs are selected, implementing the principal of a rotating chair in the Working Groups by which the co-chair becomes chair and a new co-chair is selected. Tadashi Takano, ISAS, becomes Working Group 1 (measurement) chair; others are: Working Group 2 (environment & database) - Hans-Heinrich Klinkrad, ESA; Working Group 3 (protection) - Jeanne Lee Crews, NASA JSC; and Working Group 4 (mitigation) Akira Takano, NASDA.

13th Inter-Agency Space Debris Coordination Meeting, February 28-March 1, 1996, Vol. I, Summaries; Vol. II, Proceedings.

February 29 *Interagency Report on Orbital Debris* 1995, an update of the 1989 document, is officially released. The report contains five specific recommendations:

- Continue and enhance orbital debris measurement, modeling, and monitoring capabilities
- Conduct a focused study on orbital debris and emerging LEO satellite systems
- Develop government/industry design guidelines on orbital debris
- Develop a strategy for international orbital debris discussions
- Review and update U.S. orbital debris policy

Interagency Report on Orbital Debris, Office of Science and Technology Policy, November 1989, p. 6.

March Donald Kessler retires as NASA's Chief Scientist for Orbital Debris, though he continues his work as a consultant. In June, Nicholas Johnson is hired from industry to take up the post. NASA considered the position sufficiently important to hire Johnson despite an agency-wide hiring freeze.

March Russian analysis indicates that NaK droplets spilled in orbit by RORSAT Bouk nuclear reactors will reach temperatures of 1050 deg K in sunlight. This would cause them to evaporate so rapidly that they should not be detectable in orbit.

The Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites, D. J. Kessler, M. J. Matney, R. C. Reynolds, R. P. Bernhard, E. G. Stansbery, N. L. Johnson, A. E. Potter, D. Anz-Meador, JSC-27737, NASA JSC, February 21, 1997; "About the Equilibrium Temperature of K-Na Droplets in the Near-Earth Orbits," S. A. Meshcheryakov, *Orbital Debris Monitor*, April 1, 1996, pp. 12-13; interview, David S. F. Portree with Donald Kessler, November 25, 1997.

March 12 The Chinese FSW 1-5 (China 40) photo-reconnaissance satellite was launched into a 56.5-deg orbit by a Long March 2-C rocket on October 8, 1993. The conical satellite, which consisted of a 650-kg reentry capsule and an equipment module, was designed to photograph targets on Earth for up to 10 days then return its exposed film to China for analysis. FSW 1-5 was commanded to reenter on October 18, but its retrorockets were pointed 90 deg. from the planned direction at ignition. The equipment module separated automatically and reentered on October 28, but the 1.5-m-long-by-1.6 m-wide reentry module was boosted into a higher orbit. The capsule was, of course, designed to survive reentry, so a world-wide effort to predict FSW 1-5's impact time and location commenced in late 1995. On March 11, 1996, 14 hours before reentry, the tumbling capsule was in a 115-by-199-km orbit. Its last orbit is almost entirely over water. For a time it appears that it might strike Alaska. On this date FSW 1-5 reenters off Brazil and crashes at about 645 kph into the South Atlantic at 23 deg south, 20 deg west, about 2000 km from South America.

"FSW-1 Sinks in Atlantic," *Aviation Week & Space Technology*, March 18, 1996, p. 62; United States Space Command News Release, No. 10-96, "Chinese

Satellite Entry," March 11, 1996; European Space Agency Information Note No. 13, March 11, 1996.

March 22-31

Atlantis docks with Mir on March 24. On March 27, STS-76 astronauts Rich Clifford and Linda Godwin perform a spacewalk to install the Mir Environmental Effects Payload (MEEP) on the outside of the Docking Module delivered during STS-74 in November. The main orbital debris experiment on MEEP is the JSC-built Orbital Debris Collector (ODC), a pair of capture cells containing 72 low-density silicon dioxide Aerogel tiles. Each tile is a 9.53-mm square 1.27-cm thick. Together the 72 tiles weigh only 166 grams. In a continuation of DTO 1118, STS-76 crewmembers snap 180 35-mm and 1100 70-mm photos of Mir's exterior. Atlantis undocks on March 29. One window is replaced after STS-76 due to orbital debris damage.

"Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson, Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, 27 Jul - 1 Aug 97, San Diego, CA; *Walking to Olympus: An EVA Chronology*, David S. F. Portree and Robert C. Trevino, Monographs in Aerospace History #7, NASA Headquarters, October 1997, pp. 119-120.

March 28

NASDA approves STD-18, *Space Debris Mitigation Standard*, which focuses largely on post-mission disposal. NASDA's Reliability Assurance Department launched work in 1993 on the STD-18 by creating a Space Debris Study Group. The Group included representatives from major Japanese industrial firms (and NASDA contractors) such as Mitsubishi Heavy Industries, Toshiba, Nissan Motor Co., Ishikawazima-Harima Heavy Industries, and Nippon Electric Co., as well as Kyushu University. The Group examined NASA Safety Standard 1740.14 (August 1995). STD-18 requires that GEO satellites be reorbited to 200 km above GEO at end of life, not the 300 km required by ITU and NASA.

"NASDA Space Debris Mitigation Standard," IAF-96-V.6.06, A. Kato, 47th International Astronautical Congress, October 7-11, 1996, Beijing, China.

April 1-4

The NRC holds its first meeting in its study of ISS and orbital debris. George Gleghorn, retired TRW Space and Technology Group vice president and chief of engineering, is committee chair.

April 24

The Department of Defense launches the MSX satellite on a Delta II rocket into a 902-km-by-911-km sun-synchronous orbit at 99.4 deg of inclination. MSX includes three orbital debris experiments. After deploying the satellite, the Delta II upper stage performs a propellant depletion burn to avoid explosion.

Orbital Debris Quarterly News, Vol. 2, Issue 2, April-June 1997.

May 10

Eric Christiansen, JSC HIT-F, describes recent damage to Shuttle orbiter surfaces and windows in a presentation to Space Shuttle Program manager Tommy Holloway. The presentation is one of many made to Shuttle and ISS management as part of an on-going NASA Orbital Debris Program effort to reinforce the orbiters' radiators and wing leading edges. Christiansen cites Shuttle missions STS-72, STS-73, and STS-75, and reports that improved inspections beginning in early 1994 account for some of the apparent increase in orbital debris damage to the orbiter. He states that "flight attitude is the major driver on window damage," pointing out that there is a factor of 20 difference in the number of post-flight window replacements between the best and worst attitudes, and points to effectiveness of Flight Rule 2-77 (November 1992) which governs orbiter attitude.

"Orbital Debris Damage," presentation materials, Eric Christiansen, May 10, 1996; interview, Joseph P. Loftus, Jr., December 31, 1997; interview David S. F. Portree with Joseph P. Loftus, Jr., and Nicholas Johnson, January 30, 1998.

June NASA JSC launches the *Orbital Debris Quarterly News.*

June 3 Shuttle Program manager Tommy Holloway and Randy Brinkley, ISS Program manager, send a joint letter to NASA JSC director George Abbey pointing out that plans to close the HIT-F at JSC and transfer its hypervelocity test responsibilities to JSC's White Sands Test Facility (WSTF) in New Mexico, as recommended by the NASA Facilities Consolidation Committee, run counter to recommendations made in reports of the NRC (April 1995) and the Inter-Agency Group (Space) (November 1995). HIT-F transfer occurs officially on February 2, 1998, when the HIT-F ceases light-gas gun testing. The lab, renamed the Hypervelocity Impact Technology Facility (HIT-F), continues to provide meteoroid and orbital debris risk assessments and protection concepts for spacecraft using data from light-gas guns at WSTF and shaped-charge data from Southwest Research Institute. The HIT-F's .50-caliber gun is shipped to WSTF, and its .17-caliber gun is transferred to Rice University in Houston. The lab performed 6891 tests at JSC on spacecraft materials and components since it was established in 1982.

"Hypervelocity Impact Facilities and Orbital Debris Flight Safety Issues," memorandum, MA/Manager, Space Shuttle Program to OA/Manager, Space Station Program, to AA/Director, NASA JSC, June 3, 1996; "Hypervelocity Impact Technology Facility (HIT-F) Historical Notes," Eric Christiansen, March 3, 1998.

June 4 The Hydrazine Auxiliary Propulsion System (HAPS) monopropellant fourth stage of the winged Pegasus XL launch vehicle used to place STEP II satellite into orbit on May 18 ruptures at an altitude of 625 km. HAPS was the first composite material upper stage. Although the stage is roughly the size of an oil drum and has a dry mass of only 97 kg, the explosion produces more than 700 debris objects trackable by the SSN. In terms of number of debris fragments cataloged, this is the worst satellite breakup to date. The many fragments decay from orbit slowly – of the 683 objects catalogued, 63 percent remain in orbit 18 months after the breakup.

"Analysis of the Pegasus Breakup," AAS 97-641, James G. Miller, paper presented at AAS Astrodynamics Conference, Sun Valley, Idaho, August 5, 1997; *Orbital Debris Quarterly News*, Vol. 2, Issue 1, January-March 1997; *Orbital Debris Quarterly News*, Vol. 3, No. 1, January-March 1998.

July 17-18 The IAA, International Astronautical Federation (IAF), IAU, and U.N. Office for Outer Space Affairs sponsor the orbital debris meeting at COSPAR XXXI in Birmingham, UK. The meeting includes 17 invited papers, 13 contributed, and 2 posters in three sessions devoted to remote and in-situ measurements of space debris and meteoroids; modelization of particulate environment in space; and risk analysis, hypervelocity impacts, and mitigation.

Advances in Space Research, *Space Debris*, Walter Flury, editor, Vol. 16, No. 11, 1996.

July 24

CNES launched the CERISE satellite for studies of Earth's radio environment into a retrograde orbit on July 7, 1995. On this date, a 10-year-old fragment of Ariane V16 upper stage debris collides with and severs CERISE's stabilizing gravity boom at 678 km altitude, producing one debris object. The satellite remained operational with degraded perfomance. This is the first known collision between an operational spacecraft and an identified orbital debris fragment.

Interview, David S. F. Portree with Donald Kessler, November 25, 1997.

July 30

Revised Russian analysis determines that NaK droplets released by RORSATs will reach a temperature of only 293 deg K in sunlight, giving them an on-orbit lifetime before evaporation of about a century. A 1-cm NaK droplet in 950-km orbit is expected to remain in orbit for about 80 years before decaying and entering Earth's atmosphere, at which time entry heating will cause them to rapidly sublimate.

The Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites, D. J. Kessler, M. J. Matney, R. C. Reynolds, R. P. Bernhard, E. G. Stansbery, N. L. Johnson, A. E. Potter, D. Anz-Meador, JSC-27737, NASA JSC, February 21, 1997; interview, David S. F. Portree with Donald Kessler, November 25, 1997.

August

The first Characteristics and Consequences of Orbital Debris and Natural Space Impactors session is held at the SPIE (International Society of Optical Engineering) Annual Meeting in Denver.

Orbital Debris Monitor, Vol. 9(4), October 1, 1996.

August 4-7

The Haystack radar measures the Pegasus HAPS debris cloud. By mid-December more than 75 catalogued debris have decayed. Special Haystack and Goldstone observations reveal many other 3-mm-to-5-mm debris objects. Preliminary analysis reveals that the breakup doubles the orbital debris population of this size range at about 600 km altitude.

"Haystack-Pegasus Debris Measurements," Thomas Settecerri, Eugene Stansbery, John Opiela, Mark Matney, 1997 Space Control Conference, MIT, March 1997; *Orbital Debris Quarterly News*, Vol. 2, No. 1, January-March 1997.

August 14

Nicholas Johnson presents an overview of the Pegasus HAPS breakup to the 13th meeting of the STS-82 Integrated Product Team. STS-82 is the second HST servicing mission and is planned to occur in early 1997. Immediately following the HAPS breakup, the NASA Orbital Debris Program commenced intensive efforts to assess possible risk to STS-82 with special attention to spacewalk safety and collision avoidance maneuver probabilities. According to Johnson, 100-kilogram (220-lb) upper stage broke up about 25 km (15 mi) above HST's operating altitude. Modeling the amount and behavior of the many debris objects produced is challenging because HAPS breakup has several anomalous features: the number of trackable fragments produced greatly exceeds model predictions (it is an "order of magnitude too high"); radar cross-section data implies an "unusual" (large) area-to-mass ratio; and observed decay behavior "does not yet support high area-to-mass ratio" – that is, decay has occurred too slowly to imply that the fragments are large yet light. Preliminary analysis shows that HAPS debris could enter the 2-km-by-5-km-by-2-km collision avoidance box around the orbiter "several times" while it is docked to HST during an 8-day STS-82 mission, while less easily avoided "smaller HAPS debris (0.1-10 cm) maybe pose [a] significantly higher threat." Johnson points out, however, that no impacts have been detected on HST since the HAPS breakup; a fact possibly attributable to a "'noisy' quiescent state" aboard the orbiting telescope.

"Pegasus Rocket Body Breakup Influence on STS-82," N. L. Johnson, August 14, 1996.

September 14

In 1995, President Clinton directed the Office of Science and Technology Policy and National Security Council to review national space policy. As part of this comprehensive review, they incorporated recommendations contained in the November 1995 *Interagency Report on Orbital Debris* (released February 1996). On this date, President Clinton signs the new National Space Policy, which contains the following revision of the orbital debris passage contained in the 1989 final National Space Policy:

> The United States will seek to minimize the creation of space debris. NASA, the Intelligence Community, and the DoD, in cooperation with the private sector, will develop design guidelines for future government procurements of spacecraft, launch vehicles, and services. The design and operation of space tests, experiments, and systems will minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness.
>
> It is in the interest of the U.S. Government to ensure that space debris minimization practices are applied by other spacefaring nations and international organizations. The U.S. Government will take a leadership role in international fora to adopt policies and practices aimed at debris minimization and will cooperate internationally in the exchange of information on debris research and the identification of debris mitigation options.

September 16-26

On mission STS-79, Space Shuttle Atlantis docks with Mir on September 19. The orbiter's crew snaps 230 35-mm photos and 940 70-mm photographs in support of DTO 1118. During the mission a 1-mm aluminum particle hits a payload bay door and six objects conjunct within the 5-km-by-25-km-by-5-km alert box; one enters the 2-km-by-5-km-by-2-km maneuver box. After the flight, four windows are replaced because of impact damage.

"Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson, Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, 27 July - 1 Aug 97, San Diego, CA.; Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997.

1996

October The Liquid Mirror Telescope (LMT) begins operations in Cloudcroft, New Mexico. By the end of November about 30 hours of orbital debris video data are recorded. The LMT consists of a 3-m dish holding several gallons of the liquid metal mercury. The dish spins 10 times / minutes. Centrifugal force and surface tension cause the mercury to form a thin reflective surface. The telescope stares straight up to observe debris passing through its 0.5-deg field of view. The LMT is scheduled to be fitted in 1998 with a high-speed CCD camera to allow it to achieve its design goal of detecting 1-cm debris objects.

"Liquid Metal Mirror for Optical Measurements of Orbital Debris," Andrew E. Potter and Mark Mulrooney, *Advances in Space Research*, *Space Debris*, Walter Flury, editor, Vol. 16, Number 11, 1996, pp. 213-219; *Orbital Debris Quarterly News*, Vol. 2, No. 1, January-March 1997; interview David S. F. Portree with Glen Cress, January 7, 1998.

October 7-11 The 29th annual Space Safety and Rescue symposium of the IAA is held in conjunction with the 47th IAF meeting in Beijing, China. Paper topics include an overview of the recently released NASDA STD-18; debris families observed by Haystack; aluminum slag from solid rocket motors; a Japanese GEO environmental model; Italian orbital debris research; orbital debris mitigation techniques employed in Lockheed Martin launch vehicle programs; and GEO environmental management issues.

October 24 At its fifteenth meeting, Nicholas Johnson updates the STS-82 Integrated Product Team on the Pegasus HAPS debris cloud as part of ongoing intense efforts to assess the risk to STS-82, the second HST servicing mission, scheduled for early 1997. He reports that 25 debris pieces have officially decayed, while 650 pieces are being tracked. Analysis of the anomalous HAPS debris cloud continues, bringing to bear radars from all over the world. The Fylingdales radar in Britain characterized 253 catalogued pieces. The Haystack radar observed the cloud on August 6-7, while the Goldstone radar observed the cloud on October 2. Haystack determined that some objects have "dipole-like" characteristics which could produce a false indication of their actual size. Johnson states that HST still reports no debris damage. Based on the radar observations and computer modeling, Johnson reports that the probability of critical penetration during STS-82 is within established guidelines while the probability of an orbiter radiator leak caused by impact is higher than established guidelines. By February the small particle (less than 1-cm diameter) population may decrease significantly, while the large particle population is not likely to decrease.

"Update on Pegasus/HAPS Debris Cloud," N. L. Johnson, October 24, 1996.

November Nicholas Johnson gives the orbital debris Flight Readiness Review briefing for STS-80 at KSC, marking the first application of NASA's new Orbital Debris Engineering Model (ORDEM) 96 to Shuttle mission risk assessment. Unlike earlier NASA debris environment models, which were largely theoretical, ORDEM 96 is a "semi-empirical" model based on firm data, including Haystack radar observations and analysis of Solar Max, LDEF, and other returned surfaces. In December the ORDEM 96 model documentation and software are distributed to the international orbital debris community.

Interview, David S. F. Portree with Donald Kessler, November 25, 1997; interview, David S. F. Portree with Nicholas Johnson, November 6, 1997;*Or-*

bital Debris Quarterly News, Vol. 2, No. 1, January-March 1997; *A Computer-Based Orbital Debris Environment Model for Spacecraft Design and Observation in Low Earth Orbit*, D. J. Kessler, J. Zhang, M. J. Matney, P. Eichler, R. C. Reynolds, P. D. Anz-Meador, and E. G. Stansbery, NASA Technical Memorandum 104825, November 1996.

November NASA begins advising the Russians of close approaches between the Mir space station and space objects, including orbital debris, when American astronauts are on board. In Houston, MOD Flight Dynamics Officers maintain a duty rotation. When USSPACECOM determines that an object will trespass on the 5-km-by-25-km-by-5-km alert box or the 2-km-by-5-km-by-2-km maneuvere box surrounding Mir, they page the duty officer in Houston. If the conjunction meets established criteria, the Flight Dynamics Officer uses a laptop computer to establish an internet / fax link to the Flight Control Center outside Moscow, and sends one of a standard set of alert messages to the Russian flight director.

"Orbital Debris Risk Assessments and Collision Avoidance Procedures for the Space Shuttle," IAA-97-IAA.6.5.03, Joseph P. Loftus, Don J. Pearson, and Eric L. Christiansen, 48th International Astronautical Congress, October 6-10, 1997, Turin, Italy; interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997.

November 1 Space Shuttle Meteoroid and Orbital Debris Damage Assessment Team (the Schneider Committee) makes its final presentation to Shuttle management on this date. The team reaches its conclusions based on hypervelocity impact testing in the JSC HIT-F, application of a methodology developed by the U.S. Navy to assess aircraft survivability, and tests and modeling performed at orbiter prime contractor Rockwell Corporation. The Schneider Committee reports that

- the orbiter's twin door-mounted radiators present the greatest threat of early mission termination because a single puncture can drain an entire radiator (fig. 9)

- Reinforced Carbon-Carbon wing leading edge and nose cap penetrations could lead to reentry burn-through and damage to the orbiter's aluminum structure, though with a reasonable chance of survivability depending on location

and recommends that Shuttle management

- place thin aluminum foil over radiator tubes to shield them

- fit a "flexible beanie cap" over each of the tanks located beneath the orbiter payload bay floor

Interview, David S. F. Portree with Donald Kessler, November 25, 1997; "Space Shuttle Meteoroid and Debris Damage Team," memorandum to distribution, MA/Manager, Space Shuttle Program to Distribution, September 28, 1995; *Space Shuttle Meteoroid and Orbital Debris Damage Assessment Team Final Presentation*, presentation materials, November 1, 1996; "Shuttle Modifications for Station Support," IAA-97-IAF.I.3.08, Joseph P. Loftus, Eric L. Christiansen, and William C. Schneider, 48th International Astronautical Congress, October 6-10, 1997, Turin, Italy.

1996

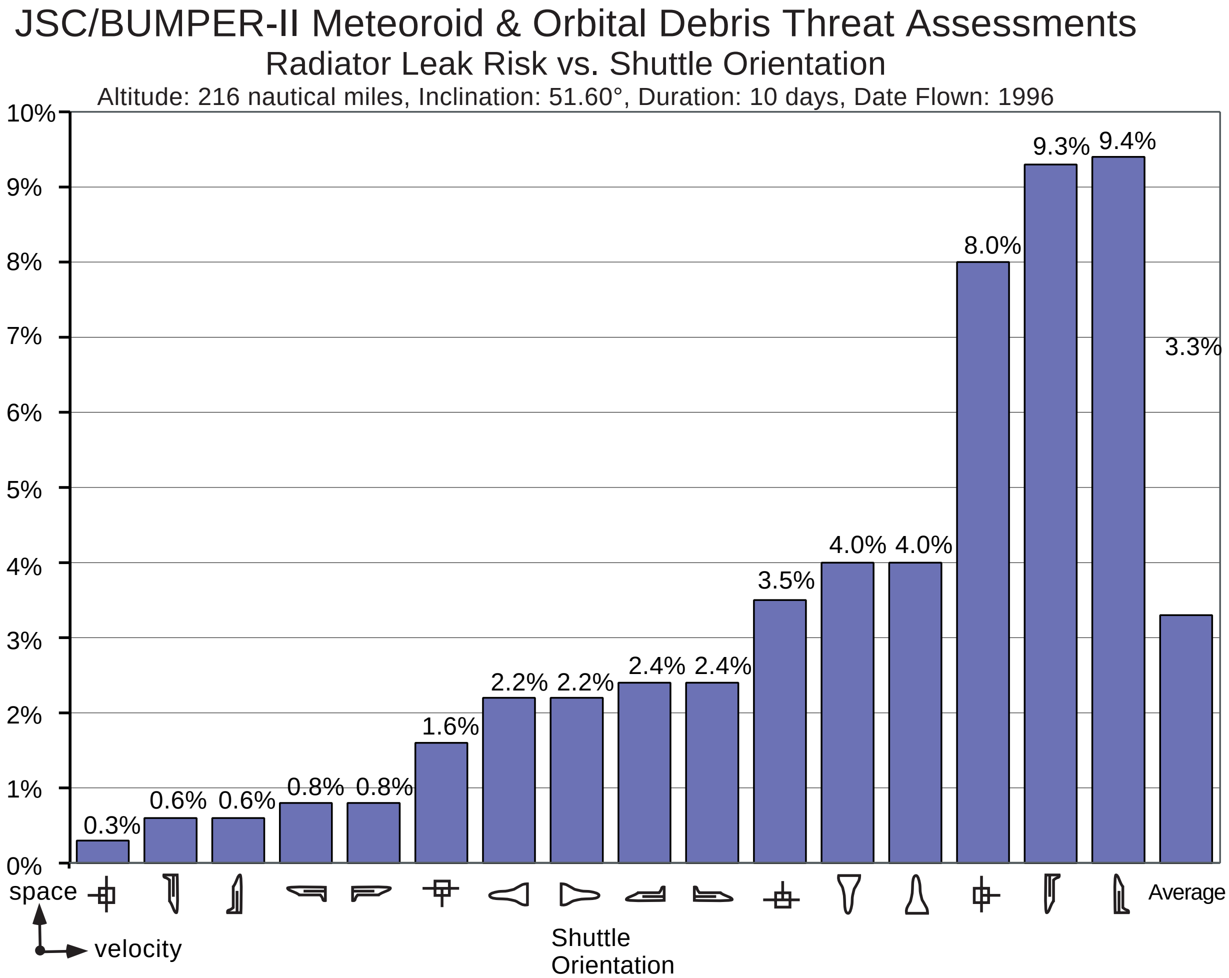

Figure 9.

The Shuttle orbiter has four radiator panels attached to the inside surface of its twin payload bay doors. The doors remain open in orbit so the radiators can reject heat produced by the orbiter's systems. This chart illustrates the risk that an orbital debris strike will produce a radiator leak at various orbiter attitudes. Risk was determined using the NASA Orbital Debris Program's BUMPER II computer model. Leak risk is highest when the orbiter points its payload bay in its direction of motion around the Earth, so mission planners avoid this attitude whenever possible.

November 19-December 7 Following the STS-80 mission, which occurs between these dates, two of Columbia's windows are replaced because of impact damage. As with Gemini in 1965, the window glass provides an excellent catch medium for hypervelocity particles. Researchers locate 51 window pits, of which 28 are subjected to SEM analysis. The impactor cannot be identified for half. Four pits contain meteoroids while paint chips and aluminum account for three pits each. Stainless steel, silver, copper, and plastic account for one pit each.

> "Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson, Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, 27 July - 1 Aug 97, San Diego, California.

Late in the year The Russians confirm that solid rocket motors boost RORSAT reactors to graveyard orbits. Aluminum oxide slag is known to leave solid rockets as they exhaust their fuel, so MIT-LL uses the Haystack radar to determine if aluminum slag is a significant component of RORSAT-associated debris. They find that the mass density of the debris is 1 gm / cm – inconsistent with aluminum oxide (4 gm / cm), but consistent with NaK. The debris is metallic and spherical – also consistent with NaK droplets. In addition, the debris quantity observed is not consistent with amount of slag expected from RORSAT solid rocket motors.

> "The Search for a Previously Unknown Source of Orbital Debris: The Possibility of a Coolant Leak in Radar Ocean Reconnaissance Satellites," IAA-97-IAA.6.3.03, D. J. Kessler, M. J. Matney, R. C. Reynolds, R. P. Bernhard, E. G. Stansbery, N. L. Johnson, A. E. Potter, D. Anz-Meador, presented at the 48th International Astronautical Congress, October 6-10, 1997, Turin, Italy; interview, David S. F. Portree with Donald Kessler, November 25, 1997.

1997

End of year launches reaching Earth orbit or beyond (since 1957)	8544
End of year satellites (objects in orbit)	3897

January *Orbital Debris Monitor* ceases publication after nine years when its editor and founder, Darren McKnight, moves on to other pursuits.

January 8 The NRC releases its report *Protecting the Space Station from Meteoroids and Orbital Debris*. The study committee finds that

> Overall efforts to protect the station have been extensive and thorough. However, the space station will be particularly vulnerable to collisions because of its size and because it will be in orbit for at least 15 years. Space station managers need to take extra precautions to reduce the risk of harm to the space station and its crew. The success of these precautions will depend on continued international efforts to reduce the amount of new debris - such as fragments from satellite or rocket body breakups - left behind from other missions.

The NASA-funded report recommends that

- Protecting the Russian-built Service Module – the station's first habitable volume – must be made a priority. The Russian segment is not as well shielded as the U.S. segment and international modules, and thus more vulnerable to impacts.

- NASA needs to perform more meteoroid and orbital debris shield testing.

- Space suit penetration risk must be reassessed; recent studies indicate that the small debris most likely to puncture a suit could be up to three times more common than previously believed.

- The ISS partners need to prepare for problems that can result from meteoroid and orbital debris impact other than catastrophic depressurization, such as short circuiting and power loss caused by solar array damage. In addition, better coordination of emergency procedures is required.

- Situations that prevent prompt ISS collision avoidance maneuvers when the SSN sounds a warning must be resolved. For example, the station is not meant to be moved while a Shuttle is docked.

- Efforts should be made to reduce the expected number of false collision warnings released by the SSN. Currently these might force the station to move more than the planned six times per year.

Protecting the Space Station from Meteoroids and Orbital Debris, National Research Council, 1997.

January 12-22 Atlantis remains docked with Mir from January 15 through January 20 during the STS-81 mission. The crew snaps 500 35-mm and 400 70-mm photos of Mir's exterior in support of DTO 1118.

"Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson, Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, 27 Jul - 1 Aug 97, San Diego, CA.

January 22 An upper stage propellant tank of the Delta II rocket that launched the MSX satellite on April 24, 1996, survives reentry on this date to impact outside Georgetown, Texas, near the state capital of Austin. The stainless steel tank weighs 250 kg (550 lb). A 30-kg (66-lb) spherical helium pressurant tank made of titanium survives to land near Seguin, Texas. After delivering MSX to 902-km-by-911-km sun-synchronous orbit at 99.4 deg of inclination, the upper stage performed a propellant depletion burn that placed it in a 207-km-by-860-km orbit and reduced its lifetime to about 9 months. Both tanks were transferred to JSC for inspection and analysis.

Orbital Debris Quarterly News, Vol. 2, Issue 2, April-June 1997; "Delta Upper Stage Crashes in Texas Field," Leonard David, *Space News*, February 24-March 2, 1997, p. 4; interview, David S. F. Portree with Nicholas Johnson, November 6, 1997.

January 27

Eric Christiansen and Nicholas Johnson present the orbital debris / meteoroid risk assessment for the STS-82 Flight Readiness Review. STS-82, the second HST servicing mission, will spend 9.7 days in 583-km (315-mi) orbit at 28.5 deg of inclination. During that time, the orbiter Discovery will spend 2.5 days with its wing pointed generally in the direction of motion and its payload bay toward Earth, and 5 days with its tail pointed in the direction of motion and its payload bay pointed toward Earth. Christiansen and Johnson report that 630 of 750 trackable Pegasus / HAPS debris remain in orbit, of which 480 intersect HST's orbit. However, to date HST has suffered no known impacts from HAPS debris. They state that, based on their analysis, the probabilities of critical penetration and radiator leak caused by impact for the mission are within established Shuttle guidelines. However, the probability that an object will penetrate the 2-km-by-5-km-by-2-km maneuver box during the flight is 86 percent, while the probability that a window will need to be replaced after the flight is 60 percent. They recommend that STS-82 is "Ready to Fly."

"STS-82 Flight Readiness Review: Orbital Debris/Meteoroid Risk Assessment," E. L. Christiansen and N. Johnson, January 27, 1997.

February 6

Citing cost reduction efforts in the wake of the Cold War, the Department of Defense closes the SSN's dish radar at Pirinclik, Turkey. Pirinclik, the first radar to detect the breakup of the Ariane V16 upper stage (1986), is only the latest in a series of orbital debris monitoring facilities fallen victim to cost cutting. These included: the GEODSS II optical telescope facility at Taegu, South Korea, closed October 15, 1993; the Saipan Island dish radar, closed November 1, 1993; the COBRA DANE phase array radar at Shemya, Alaska, closed April 1, 1994; and the PAVE PAWS SE and SW phase array radars at Robins AFB in Georgia and Eldorado, Texas, respectively, closed September 1, 1995.

February 11-21

STS-82, the second HST servicing mission, includes five EVAs by four astronauts in Discovery's payload bay. Modeling and special observations using the Goldstone and Haystack radars indicate that the Pegasus / HAPS explosion (June 4, 1996) doubled the debris flux at HST's altitude. During the flight ten conjunctions occur within the 5-km-by-25-km-by-5-km alert box; two occur within the 2-km-by-5-km-by-2-km maneuver box. Discovery maneuvers to avoid one, a piece of Pegasus / HAPS debris. The other debris fragment (Thor-Ablestar debris from the 1960s) is predicted to miss the orbiter by 1.9 km, so no avoidance maneuver occurs.

Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997; *Walking to Olympus: An EVA Chronology*, David S. F. Portree and Robert C. Trevino, Monographs in Aerospace History #7, NASA Headquarters, October 1997, pp. 119-120.

February 17-28

IADC representatives Walter Flury, ESA, and George Levin, NASA, address the S & T Subcommittee of U.N. COPUOS during its 34th session. The S & T Subcommittee agrees to continue cooperation with IADC in 1998. According to the nominal 5-year plan established in 1995, this year's meeting is given over to orbital debris modeling. The IAA becomes an official observer, and A. Kato, NASDA, briefs the Subcommittee on NASDA STD-18.

"The Role of the Scientific & Technical Subcommittee of UN-COPUOS for the

Space Debris Work of the United Nations," Dietrich Rex; *NASDA Space Debris Mitigation Standard*, NASDA-STD-18, A. Kato, NASDA.

February 28 NASA Administrator Daniel Goldin and U.S. Air Force General Howell Estes met at NASA Headquarters to sign a Memorandum of Agreement establishing the NASA / Air Force Space Command Partnership Council. The Council has implications for NASA use of DoD orbital debris tracking resources.

Memorandum to distribution from NASA/AT/Associate Deputy Administrator (Technical) and AFSPC/XP/Acting Director for Plans and Programs, November 24, 1997.

March 17-19 The 2nd European Conference on Space Debris takes place at ESOC, Darmstadt, Germany. The conference, organized by Walter Flury, ESA, is a follow-on to the 1993 meeting, and is co-sponsored by ASI, BNSC, CNES, DARA, and IAA. More than 200 orbital debris experts from 18 countries attend and present papers on a broad range of debris topics.

Proceedings of the Second European Conference on Space Debris, ESA SP-393 (SD-02), May 1997.

March 20-21 The 14th IADC meeting is held in conjunction with the 2nd European Conference on Space Debris in Darmstadt, Germany. Germany becomes an IADC member, bringing membership to nine. The organization makes RORSAT NaK study an IADC action item, adopts a uniform list of satellite breakups, and reviews common database work. The database will be made available on an ESA-based website, and will contain data on solar and geomagnetic activity, launch sites and launch vehicles, spacecraft and rocket body geometric and radar cross-section descriptions, the uniform list of satellite breakups, and other data. The IADC also discusses plans for an international GEO search campaign set to commence in October, and reaches preliminary consensus on a risk object reentry notification system architecture. The U.S. SSN and Russian SSS will provide routine tracking data to the IADC risk object database.

Orbital Debris Quarterly News, Vol. 2, Issue 2, April-June 1997.

April-June Albert Jackson and Ronnie Bernhard, Lockheed Martin, report in *Orbital Debris Quarterly News* that 86 percent of the approximately 1000 impact pits found on LDEF's trailing edge can be attributed to micron-size aluminum and aluminum oxide particles from solid rocket motors.

Orbital Debris Quarterly News, Vol. 2, Issue 2, April-June 1997.

April 3 On February 28, NASA Administrator Daniel Goldin and U.S. Air Force General Howell Estes met at NASA Headquarters in Washington, D.C., to sign a Memorandum of Agreement establishing the NASA / U.S. Air Force Space Command Partnership Council. On this date, the first formal meeting of the Partnership Council occurs at Air Force Space Command Headquarters in Colorado. Representatives of the two organizations establish seven task teams, of which two, "Space Debris" and "Cooperation on Space Environment," have implications for orbital debris.

Memorandum to distribution from NASA/AT/Associate Deputy Administrator

(Technical) and AFSPC/XP/Acting Director for Plans and Programs, November 24, 1997.

April 27-28 The NRC Committee on Space Shuttle Meteoroid / Debris Risk Management holds its first meeting in Washington, D.C. Former Shuttle astronaut Rick Hauck is chair. NASA presents its strategy for Shuttle meteoroid and orbital debris risk management on April 27, and the committee develops a study plan and report outline on April 28.

Protecting the Space Shuttle from Meteoroids and Orbital Debris, National Research Council, 1997.

May The HIT-F issues a report documenting 49 tests on Shuttle Extravehicular Mobility Unit space suit materials and ballistic limit equations performed for the EVA Project Office and NASA JSC. The HIT-F fired projectiles of different sizes at speeds of up to 7.29 km / second at suit materials, glove fingers, and the glove gauntlet at angles of 0 deg, 30 deg, 45 deg, and 60 deg. During ISS assembly U.S. astronauts will accumulate about 500 clock hours of EVA experience.

Hypervelocity Impact tests of Extravehicular Mobility Unit (EMU) (Space Suit) Material Samples, Part 1, Larry Jay Friesen and Eric Christiansen, JSC-27856, May 1997.

May 5 A Delta II rocket launches the first five satellites of the new Iridium satellite constellation. Iridium, built by Motorola and owned and operated by Iridium LLC, is the latest in a series of constellations launched over the past 30 years. A Russian Proton rocket launches seven more Iridium satellites on June 18.

Commercial Satellite Constellations and Orbital Debris

Technology breakthroughs have produced satellites not much larger and heavier than the “grapefruits” launched by the U.S. in the early days of the Space Age, yet orders of magnitude more capable and less costly. The confluence of these small satellites with economical expendable launch systems, some so affordable that university science departments can purchase flights, has produced a new arena for space commerce – commercial communication satellite constellations in LEO.

In January 1995, the U.S. firm Final Analysis, Inc. became the first to test this new arena’s potential with the first launch (on a Russian Cosmos rocket) of its FAIsat constellation. The U.S. company OrbComm started its Pegasus-launched OrbComm constellation in May 1995, and Russia began building up the Gonets (“messenger”) constellation in February 1996. But a case can be made that launch of the first five Motorola-built Iridium satellites on May 5, 1997, marked the start of the full exploitation of this market’s potential.

LEO satellite constellations are not a new phenomenon. Since the early 1960s, literally hundreds of satellites have been included in constellations. For example:

- 1970-1992 - The Russian Strela 1 military communications constellation included 360 spacecraft and 45 rocket bodies at 1450 km altitude inclined 74 deg to the equator. All Strela 1 satellites and rocket bodies remain in orbit. Strela 1 was followed by the Strela 2 and Strela 3 constellations; the Gonets constellation satellites are derived from the Strela 3 spacecraft.

- 1964-1988 - The U.S. Transit military communications constellation included 20 spacecraft and 16 rocket bodies at 900-1200 km altitude inclined 90 deg to the equator. All are still in orbit.

New generation commercial constellations include similar numbers of spacecraft operating at similar altitudes. For example:

- 1995 (first launch) - The Orbcomm constellation could include as many 84 spacecraft (36 are licensed; 48 more are proposed) in 4 planes inclined at 46 deg and 2 planes inclined at 70 deg, 775-825 km above the Earth.

- 1997 (first launch) - Iridium could include as many as 66 operational spacecraft (plus spares on orbital standby) in six planes inclined at 86.4 deg, 780 km above the Earth.

- 1998 (first launch) - Globalstar could include as many as 48 satellites in eight planes inclined at 52 deg, 1414 km above the Earth.

- 2001 (first launch) - The Teledesic constellation, one of the largest presently envisioned, could include 288 spacecraft (plus orbital standbys) in 12 planes inclined at 84.7 deg, 1372.5-1379 km above the Earth.

For several years concerns have been raised that these new generation constellations might become a new and potent orbital debris source. The constellations represent a new source of mass and cross-sectional area (and thus collision potential) put into orbit. However, older Soviet satellite systems are being retired, so the contribution to the total cross-sectional area of satellites orbiting Earth produced by the new generation commercial constellations could be minor. The current launch rate augmented by constellation launches, while greater than the rate in recent years, remains less than the rate through the 1980s up to 1991, because the Soviet Union launched more frequently than Russia does today. (In 1997, 86 launches occurred; in 1991, 117 launches took place.)

In addition, constellations contain no inherent, special threat of accelerated debris creation. Constellation satellite operators need only follow the same passivation and operational guidelines that apply to operators for all satellites.

Iridium is a model of correct commercial constellation operations. Iridium is doing more mitigation than was done with most of the historic constellations. The Iridium rocket bodies are passivated at a low altitude ensuring rapid decay. Each satellite boosts under its own power to operational altitude, then deorbits at end-of-life. Motorola, the builder of Iridium, also take care in designing their spacecraft to anticipate inherent debris or nuisance-producing problems.

Other constellation operators show a similarly enlightened attitude. The Pegasus XL-launched OrbComm satellites are essentially passivated at end of life. Teledesic has indicated that it will adhere as much as possible to NASA's passivation guidelines.

Compliance occurs so readily because these new generation constellations are managed by new generation managers aware of the significance of the orbital debris problem. Most know that early consideration of debris mitigation in new spacecraft designs minimizes the cost of implementation. They enlist orbital debris experts to make certain that their operations do not needlessly contribute to the debris environment. In addition, few operators want to create a problem which could endanger this promising new space commercial market.

Interview with Nicholas Johnson and Joseph P. Loftus, Jr., January 30, 1998; "Selected Historical LEO Constellations," Nicholas Johnson, 1997; "Orbital Debris Modeling for LEO Constellations," Paula Krisko, U.S. Government Orbital Debris Workshop for Industry, January 27-29, 1998; "Results of NASA

LEO Constellation Modeling, Robert Reynolds, U.S. Government Orbital Debris Workshop for Industry, January 27-29, 1998; "Debris Environment Interactions with Low Earth Orbit Constellations," Robert Reynolds, Anette Bade, Karl Siebold, and Nicholas Johnson, Proceedings of the Second European Conference on Space Debris, ESA SP-393 (SD-02), May 1997.

May 8-9

NASA Leonid Meteor Shower Working Group holds a meeting at NASA JSC in anticipation of a Leonid storm in 1998 or 1999. Walter Marker leads the JSC Leonids effort. The working group hears papers on the Olympus anomaly during the Perseids on August 11, 1993, as well as Leonids papers from the University of Western Ontario Meteor Group, NASA JSC, and the National Central University of Taiwan.

Meeting packet, NASA Leonid Meteor Shower Working Group Meeting, May 8-9, 1997.

May 15-24

Atlantis docks with Mir during STS-84. The orbiter's crew snaps 830 35-mm and 160 70-mm photos in support of DTO 1118. Three objects conjunct with the orbiter within the 5-km-by-25-km-by-5-km alert box.

"Photographic surveys of the Mir space station and the detection of orbital debris and meteoroid impacts," Mike Gaunce, Robert Scharf, Nicholas Johnson, Eric Christiansen; paper presented at SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Conference on Characteristics and Consequences of Orbital Debris and Natural Space Impactors II, July 27-Aug 1, 1997, San Diego, California; Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997.

May 22

The auxiliary motor that settled propellants in the Proton Block DM fourth stage used to place the Ekran 17 satellite in GEO (1987) explodes in 310-km-by-22,975-km, 46.6-deg geosynchronous transfer orbit, producing 72 detectable debris objects. This is the fifteenth Proton auxiliary motor explosion since 1984. Normally few fragments from such breakups are catalogued, and to date these breakups appear to pose little threat.

Orbital Debris Quarterly News, Vol. 2, Issue 3, July-September 1997.

May 29

NASA Policy Directive (NPD) 8710.3 is issued on this date to replace NMI 1700.8 (April 1993). The new NPD, effective through May 29, 2002, states that NASA orbital debris policy is to

- employ design and operation practices that limit the generation of orbital debris, consistent with mission requirements and cost-effectiveness.

- conduct a formal assessment in accordance with NASA Safety Standard (NSS) 1740.14 "Guidelines and Assessment Procedures for Limiting Orbital Debris," 1995, on each NASA program / project, of debris generation potential and debris mitigation options. As a minimum, the assessment should address the potential for orbital debris generation in both nominal operation and malfunction conditions; the potential for orbit debris generation due to on-orbit impact with existing space debris (natural or human-generated) or other orbiting space systems; and postmission disposal.

- establish and implement additional debris mitigation measures when the assessed debris contributions are not considered acceptable.

NASA NPD 8710.3, May 29, 1997

June Mars TransHab Design Team formed in March 1997 as part of efforts to develop a low-cost, inflatable Mars transit habitat that could also serve as an ISS module. One mission profile has a crewless Transhab spiraling slowly out from LEO over nine months using a solar electric propulsion system. The crew boards in high Earth orbit just before the vehicle leaves Earth orbit for Mars. While reducing the amount of mass which must be launched from Earth, this profile means that the vehicle lingers in several altitude regimes with relatively dense orbital debris concentrations. A deployable Multi-Shock Shield covers the inflatable Transhab's skin. The shield consists of three Nextel fabric bumpers separated from each other by 10 cm of open-cell foam hollowed by cylindrical volumes over a rear wall of 5 layers of Kevlar. Seven Transhab HIT-F tests were performed – four of the baseline shield and three with varying amounts of foam and adhesive. In the four baseline tests, neither a 157.7 mg object moving at 6.74 km / second nor a 375.2 mg object moving at 6.82 km / second penetrated the rearwall. Probability of no penetration is ~98 percent over an entire Mars flight.

"TransHab Overview," Donna Fender, NASA JSC Engineering Directorate, August 5, 1997; *Mars TransHab Meteoroid and Orbital Debris Shield Performance Assessment*, JSC 27892, Glen Shortliffe and Eric Christiansen, June 1997; *Orbital Debris Quarterly News*, Vol. 2, Issue 3, July-September 1997.

June 16-18 The NRC Committee on Space Shuttle Meteoroid / Debris Risk Management holds its second meeting in Houston, Texas. The Committee hears about the EVA astronaut vulnerability to meteoroids and orbital debris.

Protecting the Space Shuttle from Meteoroids and Orbital Debris, National Research Council, 1997.

June 26 Cosmos 2313, an ELINT ocean reconnaissance satellite (EORSAT) breaks up at an altitude of 285 km in a 210-km-by-325-km orbit at 65 deg of inclination, close to the 300-km orbit planned for orbiter Columbia during STS-94, due to launch on July 1. The 3000-kg EORSAT remains largely intact but produces about 90 detectable debris pieces, most of which reenter by June 30. Following an alert by U.S. Navy Space Command, the NASA Orbital Debris Program determines that critical component and radiator tube penetration risks remain within Shuttle program guidelines. The team also assesses the likelihood that avoidance maneuvers will be required during STS-94. The flight is a microgravity research mission with objectives which can be compromised by collision avoidance maneuvers.

Orbital Debris Quarterly News, Vol. 2, Issue 3, July-September 1997.

June 27 NASA approved the "Joint NASA / DoD Work Plan on Orbital Debris" in June 1996; on this date the Department of Defense adopts it.

July 11 George Levin retires, effectively transferring the NASA Orbital Debris Program manager position to Nicholas Johnson at JSC. Official transfer takes place through a letter from JSC Director George Abbey to Wilbur Trafton of NASA Headquarters on September 15.

July 27-August 1 The second Characteristics and Consequences of Orbital Debris and Natural Space Impactors session is held on July 28 as part of the SPIE International Symposium on Optical Science, Engineering, and Instrumentation in San Diego, California.

August NASA MSFC publishes a meteoroid and orbital debris primer as part of its meteoroid and orbital debris technology program. MSFC work complements the larger NASA Orbital Debris Program managed at NASA JSC.

"Meteoroids and Orbital Debris Effects on Spacecraft," NASA RP 1408, C. A. Belk, J. H. Robinson, M. B. Alexander, W. J. Cooke, and S. D. Pavelitz

August 7-19 During STS-85 a debris object passes within 0.2 km of the Shuttle Payload Satellite (SPAS) freeflyer deployed from orbiter Discovery. SPAS leads orbiter by about 50 km at this time.

Memorandum with attachments, Steven Stich, Lead, Orbit Flight Dynamics Group, "Conjunction Summary for STS-26 through STS-85," September 17, 1997.

September 3-4 NASA and U.S. Air Force representatives meet with Canadian meteoroid experts in London, Ontario, Canada to develop a Tripartite Leonids Meteor Storm Campaign to occur in November 1997. The purpose of the campaign is to develop higher confidence threat assessments for the potential 1998-2000 Leonids storms.

"NASA/AFSPC Space Debris Task Team Status Report," October 22, 1997.

September 15 Mir's crew, which includes a U.S. astronaut, boards its Soyuz-TM ferry as a precaution during a close conjunction with the U.S. MSTI-2 satellite. Their action is based on NASA advice using USSPACECOM data. MSTI-2 launched on May 9, 1994, on the last Scout rocket. NASA sent the Russians eight advisories between November 1996 and October 1997, but this is the first for which action is taken.

"Orbital Debris Risk Assessments and Collision Avoidance Procedures for the Space Shuttle," IAA-97-IAA.6.5.03, Joseph P. Loftus, Jr., Don J. Pearson, and Eric L. Christiansen, 48th International Astronautical Congress, October 6-10, 1997, Turin, Italy.

September 16 Russia intentionally explodes a military reconnaissance satellite in LEO for the first time in 4 years at an altitude of 230 km. Cosmos 2343, launched May 15, 1997, is the latest in a series of satellites designed to be destroyed at end-of-life. The SSN characterizes orbits of 32 debris objects within 48 hours of the explosion. NASA JSC determines that 70 percent of the threat to the Mir station passes within 24 hours, and that the short-lived Cosmos 2343 debris cloud is unlikely to pose a threat to the STS-86 Shuttle mission.

"Intentional LEO Spacecraft Breakup," *Orbital Debris Quarterly News*, Vol. 2, No. 4, October-December 1997; Joint NASA/DoD Work Plan on Orbital Debris, June 27, 1997, Final Draft.

September 25-October 6

Prior to the STS-86 mission, the HIT-F updated its models of meteoroid and orbital debris risks to the Shuttle to take into account new Mir docking attitudes. A total of 77 attitude / altitude combinations are evaluated using BUMPER II calculations, making STS-86 the most computationally intensive mission to date. During STS-86 Atlantis docks with Mir and astronaut Scott Parazynski and cosmonaut Vladimir Titov perform a joint EVA to recover the MEEP from Mir's Docking Module for return to Earth.

"Hypervelocity Impact Technology Facility (HIT-F) Historical Notes," Eric Christiansen, March 3, 1998.

October

NASA / Air Force Space Partnership Council reviews a "White Paper Study of the Design of a Collision Avoidance Network for Orbital Debris with Sizes Down to 5-cm" circulated by Space Debris Task Team. The paper notes that the SSN can monitor objects as small as 10 cm, but 0.1-cm objects can cause significant damage. It recommends a range of SSN improvement studies, as well as upgrades and use modifications for existing facilities (particularly the Eglin FPS-85, Millstone, and Cavalier radars). The paper also recommends investigation of a low-cost optical system to aid in cataloging and maintaining orbital elements for objects in high-eccentricity orbits with perigees over the southern hemisphere.

"White Paper Study of the Design of a Collision Avoidance Network for Orbital Debris with Sizes Down to 5-cm" NASA/AFSPC Partnership Council, October 1997.

October

The GEO observation campaign begins under auspices of the IADC. U.S. observations occur at Cloudcroft, New Mexico, using the 32-cm CDT instrument, which has a 1.6-deg field of view and is capable of imaging 16-magnitude stars with a 20-second exposure.

Interview, David S. F. Portree with Glen Cress, January 7, 1998.

October 3

White House Office of Science and Technology Policy director John Gibbons signs the launch approval for the Cassini Saturn probe. The spacecraft relies on RTGs containing plutonium fuel for electrical power, as have about 30 other U.S. space vehicles in the past three decades. Because Titan IV is not powerful enough to send 5300-kg (11,660-lb) Cassini on a direct trajectory to Saturn, the automated orbiter must perform gravity-assist swingbys of Venus (twice), Earth, and Jupiter. The Earth flyby is scheduled for August 18, 1999, at a distance of 1160 km (720 mi). Concern was raised about the possibility that a meteoroid might impact Cassini between the second Venus encounter and Earth flyby, causing loss of control and permitting Cassini to collide with Earth. The Interagency Nuclear Safety Review Panel, which consists of about 50 safety experts from NASA, DOE, DoD, the Environmental Protection Agency, and the Nuclear Regulatory Commission, convenes a special review panel to assess the issue. They find that a meteoroid impact that destroys the propulsion system could produce an impulse deflecting Cassini into a collision with Earth only if it occurs 50 days before Earth swingby. The probability of this occurrence is estimated at less than 1 in 1,000,000. Cassini departs Earth with a cargo of a dozen scientific instruments and ESA's Huyghens Titan probe on October 15. Cassini will begin the first in-depth Saturn exploration in 2004.

"NASA Receives Approval to Launch Cassini Mission," NASA press release 97-225, October 3, 1997; "Spacecraft Power for Cassini," NASA Fact Sheet, February 1996; "The Cassini Mission to Saturn," NASA Fact Sheet, March 1996.

October 6 The ISS Program publishes its Debris Avoidance Operations plan. ISS will always accelerate at 1 m / second to avoid conjunctions so that all avoidance maneuvers contribute to raising the station's orbit. Conjunction prediction is to be based on a new probability-based, real-time procedure in order to reduce the number of required avoidance maneuvers to six per year, assuming no breakups in a near or intersecting orbit. Probability calculations will be made at the Space Station Control Center at NASA JSC. If the Shuttle system of alert and maneuver boxes were used, 20 to 40 avoidance maneuvers per year might be required. This is intolerable because ISS requires a 0.60 probability of six uninterrupted 30-day microgravity periods / year and because the amount of propellant needed would be prohibitive.

"Orbital Debris Risk Assessments and Collision Avoidance Procedures for the Space Shuttle," IAA-97-IAA.6.5.03, Joseph P. Loftus, Don J. Pearson, and Eric L. Christiansen, 48th International Astronautical Congress, October 6-10, 1997, Turin, Italy.

October 6-10 The 30th annual Space Safety and Rescue symposium of the International Academy of Astronautics held in conjunction with the 48th International Astronautical Federation meeting in Turin, Italy. Paper topics include SFU post-flight analyses; joint European-Russian work to perform in-situ measurement of meteoroids and space debris in GEO; constellations and orbital debris; large debris reentries; and probable NaK coolant leaks from Soviet RORSATs.

October 10 The MEEP arrives at NASA JSC, where the ODC is removed and subjected to analysis in the Facility for the Optical Inspection of Large Surfaces laboratory. In November researchers release a 30-day report containing results of their large-scale inspection of the two ODC Aerogel trays. They report that they found a total of 86 distinct tracks (often "carrot-shaped"), 74 pits, and 191 "flakes." Some of the tracks are indicative of particle swarms.

Macroscopic Inspection of the Orbital Debris Collector Experiment (ODC) 30-Day Report, Friedrich Horz, et al.

October 22 The NASA / Air Force Space Partnership Council meets for the second time at NASA Headquarters in Washington, D.C. The "space debris" task team, co-chaired by NASA's Nicholas Johnson, and U.S. Air Force representatives Col. James Brechwald and Dr. David Spencer, reports that

- the "Joint NASA / DoD Work Plan on Orbital Debris" has been adopted
- an assessment of SSN capabilities to detect small debris has been handed off to the Joint NASA / DoD Work Plan
- NASA / DoD orbital debris mitigation guidelines were developed based on NSS 1740.14, which will be presented to industry at a NASA / DoD Workshop in January

- The NASA / DoD Workshop is in an advanced state of preparation

- NASA and DoD have become partners in the IADC; future activities are to be carried out under the NASA / DoD work plan

- NASA / U.S. Air Force Space Partnership Council / Canada Leonids Meteor Storm Campaign was established and handed over to a Tripartite Leonids Meteor Storm Campaign team

The task team takes as an action item providing an estimate of the ISS reliability improvement achievable by cataloguing objects as small as 5 cm in diameter using DoD-funded upgrades.

Memorandum to Distribution from NASA/AT/Associate Deputy Administrator (Technical) and AFSPC/XP/Acting Director for Plans and Programs, November 24, 1997.

November 3

USSPACECOM issues UPDIO-39, *Satellite Disposal Procedures*, which establishes the following end of life disposal guidelines for U.S. Department of Defense satellites:

- LEO satellites will be moved to a disposal orbit with a lifetime of no more than 25 years.

- Medium-Earth orbit satellites will be moved to circular disposal orbit at least 500 km above 12-hour orbit and 500 km below GEO.

- GEO satellites will be reboosted to a circular orbit at least 300 km above GEO.

"DoD Policy on Disposal of Satellites," *Orbital Debris Quarterly News*, Vol. 3, No. 1.

November 4-5

The Aerospace Corporation Center for Orbital and Reentry Studies holds the Aerospace Forum on Space Debris, Collision Avoidance, and Reentry Hazard. William Ailor, the Center's director, coordinates the Forum, which includes an orbital debris overview by Aerospace Corporation's Vladimir Chobotov. The Forum also includes sessions on policy by David Spencer, U.S. Air Force Phillips Laboratory, and on End-of-Mission Requirements, Reentry Prediction and Breakup, and Collision on Launch Avoidance by The Aerospace Corporation employees Spencer Campbell, Wayne Hallman, and Dan Oltrogge, respectively.

Aerospace Forum on Space Debris, Collision Avoidance, and Reentry Hazard; proceedings of a meeting held at the Aerospace Corporation Center for Orbital Debris and Reentry Studies, November 4-5, 1997.

Mid-November

Space Shuttle management elects to delay Columbia's launch on the STS-87 mission by a few days to avoid the peak of the Leonid Meteor Shower.

December

The U.S. Air Force Scientific Advisory Board reports that the SSN is inadequate to meet current and future needs and advises improvements. The board states in its report that "[t]he present radars, with some modest upgrades and proper calibration, could perform superior earth satellite surveillance, if the processing capability were updated.”

Space Surveillance, Asteroids and Comets, and Space Debris, U.S. Air Force Scientific Advisory Board, December 1997.

December 1 At the request of Subcommittee on Space and Aeronautics of the House of Representatives, the Government Accounting Office publishes its report *Space Surveillance: DoD and NASA Need Consolidated Requirements and a Coordinated Plan*. The purpose of the report is to assess

- how well DoD’s existing surveillance capabilities support DoD’s and NASA’s current and future surveillance requirements

- the extent to which potential surveillance capabilities and technologies are coordinated to provide opportunities for improvements

The report finds that the existing SSN cannot satisfy emerging requirements. In addition, potential surveillance capabilities are inadequately coordinated between the DoD branches and NASA. The report recommends that the Secretary of Defense and NASA Administrator, in coordination with Director of Central Intelligence Agency,

- establish a consolidated set of government-wide space surveillance requirements for evaluating current SSN capabilities and future SSN architectures

- develop a coordinated government-wide space surveillance plan that sets forth and evaluates alternative capabilities to support human spaceflight and emerging national security requirements, and ensures that any planned funding for space surveillance upgrades is directed toward satisfying consolidated government-wide requirements.

Space Surveillance: DoD and NASA Need Consolidated Requirements and a Coordinated Plan, GAO/NSIAD-98-42, December 1, 1997.

December 9-12 Over 90 orbital debris experts from nine member space agencies attend the 15th IADC in Houston (see Appendix 1). At the urging of the Japanese delegation, the members agree to a new policy for end of life GEO reboost to 235 km plus a distance in kilometers equal to 1000 times the area divided by mass. The IADC also establishes the orbits 200 km above or below GEO as transfer corridors for repositioning assets. Italy petitions to become an IADC member.

Interview, David S. F. Portree with Joseph P. Loftus, Jr., December 31, 1997; *Orbital Debris Quarterly News*, Vol. 3, No. 1, January-March 1998.

December 16 The NRC releases *Protecting the Space Shuttle from Meteoroids and Orbital Debris*. The report fails to take into account NASA efforts to reinforce the orbiter (figs. 10, 11) which began formally with the work of the Space Shuttle Meteoroid and Orbital Debris Damage Assessment Team in 1995. Some of its recommendations – for example, that NASA and the Department of Defense work together to satisfy NASA’s on-orbit collision avoidance requirements –

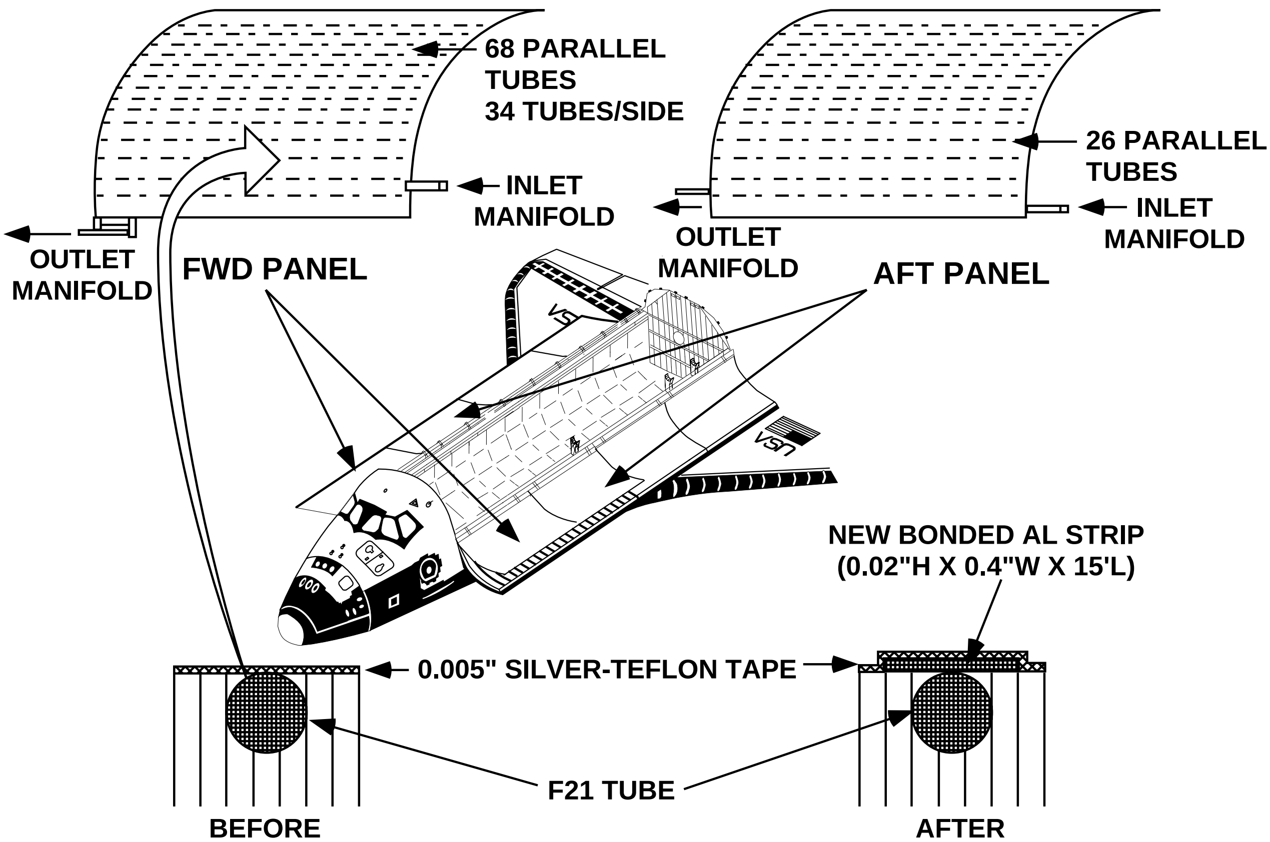

Figure 10.

The illustration above depicts the general layout of the Shuttle orbiter radiator fluid loops and steps taken to reduce their vulnerability to orbital debris. Both sides of the twin forward radiator panels reject heat, so they contain more tubes than the aft panels. Puncturing a tube can cause an entire side of the orbiter cooling system to drain, halving the spacecraft's ability to reject heat and forcing early mission termination. Beginning in 1998, NASA "armored" the tubes with 0.02-inch-thick bonded aluminum strips. The agency also added isolation valves. If an impactor penetrates the new "armor," the valves can prevent complete coolant loss on the affected side. This allows the orbiter to fall back on the flash evaporator cooling system it normally uses while the payload bay doors are closed.

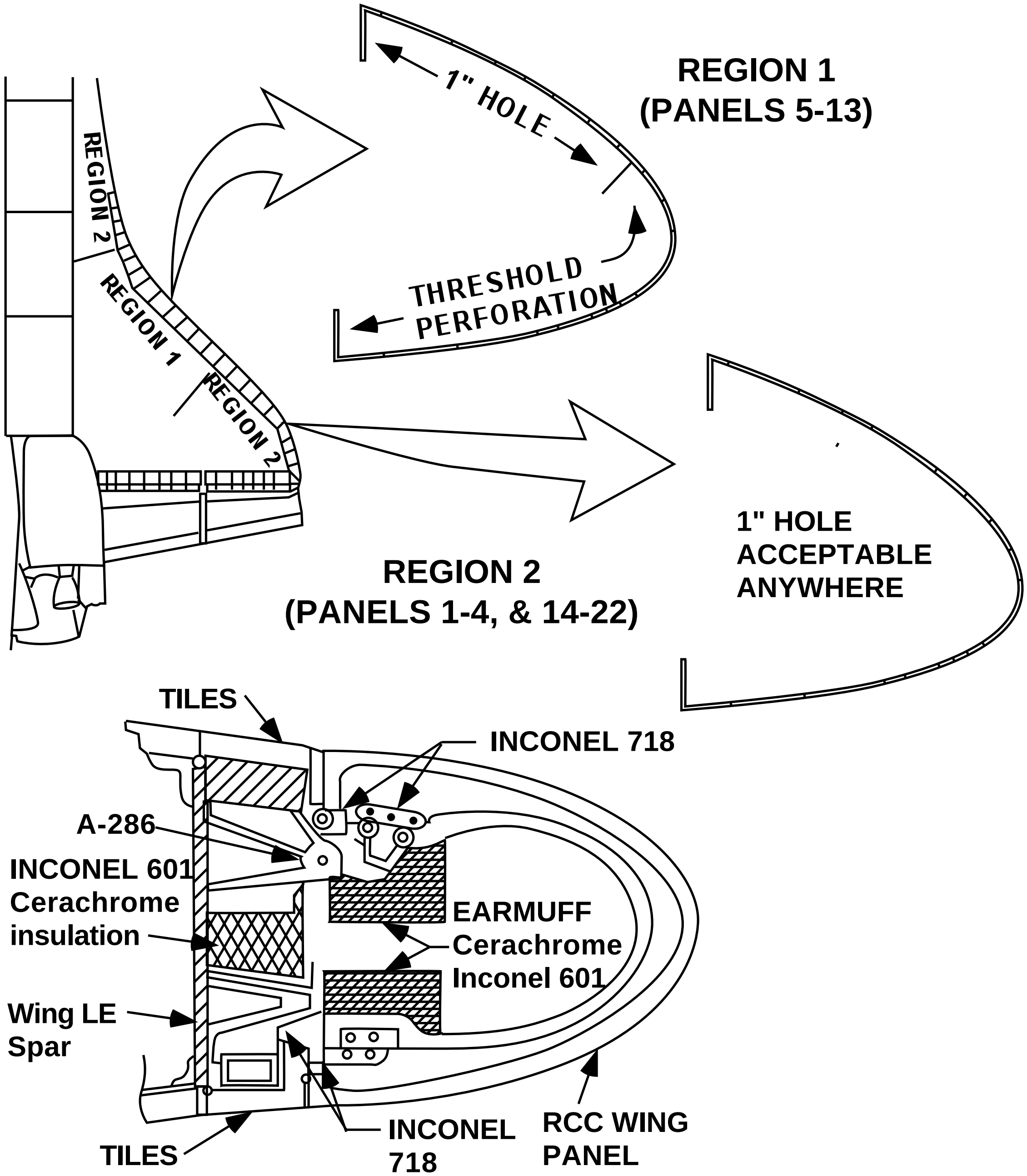

Figure 11.

The orbiter wings are highly redundant structures, so penetrations over much of the wing area do not present a safety hazard. Nevertheless, analysis indicated that damage to portions of the Reinforced Carbon-Carbon (RCC) wing leading edges could produce unacceptable wing damage. This is because a debris impact perforation small enough to be unnoticed in orbit could act as an inlet for hot plasma (ionized gas) generated during reentry. The plasma could pour into the cavity behind the RCC and impinge on the aluminum wing structure, damaging critical components. “Region 1” in the illustration above is particularly susceptible because it is located at the confluence of the orbiter bow and wing shockwaves - thus it experiences the highest reentry heating levels. NASA reinforced the wing main spar thermal insulation by adding a layer of Nextel (an alumina silicate ceramic fabric) behind the existing Inconel 601 cerachrome foil insulation within the wings. The Nextel does not prevent impact penetrations, but it does increase the ability of the wing leading edge structure to withstand entry heating.

were already underway when the report was in preparation. In addition, it promotes the misconception that the risk of critical penetration from meteoroids or orbital debris is 1 in 200 – that is, greater than the risk incurred during Shuttle ascent or descent. In a letter published in *Space News* in early February, NASA Chief Scientist for Orbital Debris Nicholas Johnson responds to this assertion, stating that

> The claim is in fact erroneous and stems from an apparent miscommunication. . .The 1-in-200 estimation of risk of critical penetration by orbital debris arose early in the NASA space shuttle orbital debris risk-assessment process. It represented a highly conservative assessment based on criterion of no penetration of the reinforced carbon-carbon material on certain portions of the leading edge of the shuttle's wing. This benchmark was used until a series of hypervelocity impact tests [in the JSC HIT-F] and thermal and structural responses determined that holes as large as several millimeters in diameter. . .will not pose a threat to crew or vehicle. . .the predicted risks from orbital debris and micrometeoroid impacts now are substantially less than those present during launch. In 1997, NASA adopted a modification to the orbiters to tolerate even larger holes without threat to the crew or vehicle, thus reducing flight risks and improving safety even further.

Protecting the Space Shuttle from Meteoroids and Orbital Debris, NRC, 1997; "Clearing Debris," Nicholas Johnson, *Space News*, January 26-February 1, 1998.

December 23 An Orbital Sciences Corporation Pegasus XL winged launcher successfully delivers eight satellites of the new OrbComm messaging satellite constellation to LEO, bringing the total number of spacecraft in the constellation to 10 (OrbComm launched the first two satellites on a Pegasus XL in April 1995). The winged Pegasus XL launcher uses a HAPS fourth stage akin to the one that ruptured in orbit in June 1996. Orbital Sciences Corporation, maker of the Pegasus XL and HAPS, traced the explosion to residual helium pressurant that may have leaked past a faulty regulator valve and repressurized the hydrazine propellant tank. The company redesigned HAPS, doing away with the helium tank in favor of a "blow-down" propellant system. On December 8, the Federal Aviation Administration (FAA) suspends Orbital Science Corporation's launch license after learning that the company does not intend to passivate the redesigned HAPS as it had agreed to do when granted its launch license in March 1997. The FAA restores the license after the company agrees to make a software fix to vent residual HAPS propellant. After delivering its payloads into a circular orbit at an altitude of 825 km, the HAPS vents residual helium, hydrazine, and nitrogen, placing itself in a 410-km-by-827-km orbit that significantly reduces its orbital lifetime.

"FAA Yanks Pegasus XL Launch License," Warren Ferster, *Space News*, December 15-21, 1997, p. 1, 20; interview, David S. F. Portree with Joseph P. Loftus, December 31, 1997; "Pegasus Upper Stage," *Orbital Debris Quarterly News*, Vol. 3, No. 1, January-March 1998.

December 25 The Proton Block DM fourth stage carrying Asiasat 3 (launched December 24) suffers apparent catastrophic failure at first geosynchronous transfer orbit apogee (35,995 km), one second into its circularization burn. The SSN spots fewer than 10 objects, of which only two are still being observed on January 9, 1998. The accident is similar to the one which befell Raduga 33 on February 19, 1996.

Email from Nicholas Johnson, January 9, 1998.

1998

January 15

Ballistic Missile Defense Organization officials announce that an unidentified orbital debris object collided with and destroyed a Minuteman III Multi-Service Launch System booster 450 km over the Kwajalein Islands, 30 minutes after launch from Vandenberg Air Force Base, California. The rocket's solid-fueled third stage had completed its mission and was falling back into the atmosphere when the reported collision occurred. Breakup of the third stage was observed by airborne optical and ground-based and sea-based radar sensors, but only one radar detected the possible debris object. The orbital debris detection was later judged erroneous.

"Minuteman Third Stages Destroyed by Orbital Debris," James Oberg, *Space News*, February 16-22, 1998, p. 3; email from Nicholas Johnson, March 5, 1998.

January 27-29

U.S. Government Orbital Debris Workshop for Industry is held in Houston. Representatives of U.S. government organizations – specifically the Department of Defense, NASA, FAA, and FCC – place emphasis on educating the growing space private sector about orbital debris. Nicholas Johnson presents an overview of the NASA Orbital Debris Program, while Ruben Van Mitchell, with DOT's Commercial Space Transportation Office presents FAA regulations. Kelli Seybolt presents the DoD perspective, and Karl Kensinger, the FCC view. Joseph Loftus reviews international orbital debris mitigation activities. Participants also review the draft U.S. Government Orbital Debris Mitigation Standard Practices and the orbital debris issues associated with low-Earth orbit satellite constellations. The workshop divides into three working groups to help foster industry inputs.

Interview, David S. F. Portree with Nicholas Johnson and Joseph P. Loftus, Jr., January 30, 1998.

Appendix 1: Participants in the 15th IADC meeting

The membership roster of the 15th IADC meeting, held in December 1997, in Houston, Texas, graphically illustrates the expansion of international orbital debris awareness over the past 37 years. Participants are grouped by delegation; individuals within each delegation may hold other affiliations.

British National Space Center

Richard J. Tremayne-Smith
Richard Crowther
Peter Hedley Stokes
Roger Walker
Malcolm Bain
David Holland
Dick James

Centre National d'Etudes Spatiale

Pierre Moskwa
Fernand Alby
Christophe Bonnal
Gilbert Marthon
Andre Rolfo
Jean Claude Mandeville
Thierry Michal
Olivier Bonfils

China National Space Administration

Qi Yongliang
Liu Yenfeng
Weng Weiliang
Wang Lizai
Lu Bo
Tu Xinying
Wu Liandam
Jian Yaowen

Deutsche Zentrum für Lufte und Raumfahrt e.V.

Detlef Alwes
Dieter Mehrholz
Frank K. Schaefer
Hans-Guenther Reimerdes

European Space Agency

Walter Flury
Hans-Heinrich Klinkrad
Gerhard Drolshagen
Ruediger Jehn
Michel Lambert
Walter Naumann
Inigo Mascaraque

Dietrich Rex
Bruno Bertotti

Indian Space Research Organization

Aiyam S. Ganeshan

Japan

Susumu Toda
Seishiro Kibe
Shunji Suematsu
Tadashi Takano
Akira Takano
Fumio Terada
Toru Tajima
Hiroyuki Konno
Syuzo Isobe
Tetsuya Yamamoto

NASA

Nicholas Johnson
Eric Christiansen
Jeanne Crews
Wayne Frazier
Justin Kerr
Joe Loftus
Walter Marker
Wendell Mendell
Gene Stansbery
Jeff Theall
Faith Vilas
Greg Olsen
Kelli Seybolt
David Spencer
Tim Payne
Taft DeVere
Firooz Allahdadi
Anthony Andrews
Kim Luu
Jeffrey Maclure
George Levin
Drew Potter
Anette Bade
Peter Eichler
Neal Hartsough
Al Jackson
Don Kessler
Ben Kirk
Paula Krisko
Mark Matney
Babara Nowakowski
John Opiela

Bob Reynolds
William Rochelle
Tom Settecerri
Karl Seibold
Alejandro Soto
Phillip Anz-Meador
Spencer Campbell
Val Chobotov
Marlon Sorge

Russian Space Agency

Vladimir Pochukaev
Sergey Chekalin
Sergey Mescheriakov
Andrey Nazarenko
Stanislav Veniaminov

Appendix 2: Breakup history

The tables that follow were produced by the NASA Orbital Debris Program based on data provided by USSPACECOM. Table 1 lists all known breakups to August 1998. Table 2 lists anomalous events — occasions when spacecraft produced trackable debris objects but evidently remained largely intact.

Table 1. All Known Breakups

EVENT NO.	SATELLITE NAME	INTERNATIONAL DESIGNATOR	US SATELLITE NUMBER	SATELLITE OWNER	SATELLITE TYPE	SATELLITE MASS (KG)	LAUNCH DATE	BREAKUP DATE	APOGEE (KM)	PERIGEE (KM)	INCLINATION (DEG)	ASSESSED CAUSE	ADDITIONAL INFORMATION
1	TRANSIT 4A R/B	1961-015C	118	USA	ROCKET BODY	625	29-Jun-61	29-Jun-61	995	880	66.8	PROPULSION	ABLESTAR STAGE
2	SPUTNIK 29	1962-057A	443	USSR	ROCKET BODY	1500	24-Oct-62	29-Oct-62	260	200	65.1	PROPULSION	MOLNIYA FINAL STAGE
3	ATLAS CENTAUR 2	1963-047A	694	USA	ROCKET BODY	4600	27-Nov-63	27-Nov-63	1785	475	30.3	PROPULSION	CENTAUR STAGE
4	COSMOS 50	1964-070A	919	USSR	PAYLOAD	4750	28-Oct-64	5-Nov-64	220	175	51.2	DELIBERATE	SELF-DESTRUCT
5	COSMOS 57	1965-012A	1093	USSR	PAYLOAD	5500	22-Feb-65	22-Feb-65	425	165	64.8	DELIBERATE	SELF-DESTRUCT
6	COSMOS 61-63 R/B	1965-020D	1270	USSR	ROCKET BODY	1600	15-Mar-65	15-Mar-65	1825	260	56.1	UNKNOWN	COSMOS SECOND STAGE
7	OV2-1/LCS 2 R/B	1965-082B	1640	USA	ROCKET BODY	2555	15-Oct-65	15-Oct-65	790	710	32.2	PROPULSION	TITAN TRANSTAGE
8	COSMOS 95	1965-088A	1706	USSR	PAYLOAD	400	4-Nov-65	15-Jan-66	300	180	48.4	UNKNOWN	
9	OPS 3031	1966-012C	2015	USA	PAYLOAD	4	15-Feb-66	15-Feb-66	270	150	96.5	UNKNOWN	INFLATABLE SPHERE
10	GEMINI 9 ATDA R/B	1966-046B	2188	USA	ROCKET BODY	3400	1-Jun-66	Jun-66	275	240	28.8	UNKNOWN	ATLAS CORE STAGE
11	AS-203	1966-059A	2289	USA	ROCKET BODY	26600	5-Jul-66	5-Jul-66	215	185	32.0	DELIBERATE	SATURN S-IVB STAGE
12	COSMOS U-1	1966-088A	2437	USSR	PAYLOAD	NA	17-Sep-66	17-Sep-66	855	140	49.6	DELIBERATE	SELF-DESTRUCT
13	COSMOS U-2	1966-101A	2536	USSR	PAYLOAD	NA	2-Nov-66	2-Nov-66	885	145	49.6	DELIBERATE	SELF-DESTRUCT
14	COSMOS 199	1968-003A	3099	USSR	PAYLOAD	5500	16-Jan-68	24-Jan-68	355	200	65.6	DELIBERATE	SELF-DESTRUCT
15	APOLLO 6 R/B	1968-025B	3171	USA	ROCKET BODY	30000	4-Apr-68	13-Apr-68	360	200	32.6	PROPULSION	SATURN S-IVB STAGE
16	COSMOS 249	1968-091A	3504	USSR	PAYLOAD	1400	20-Oct-68	20-Oct-68	2165	490	62.3	DELIBERATE	SELF-DESTRUCT
17	COSMOS 252	1968-097A	3530	USSR	PAYLOAD	1400	1-Nov-68	1-Nov-68	2140	535	62.3	DELIBERATE	SELF-DESTRUCT
18	COSMOS 248	1968-090A	3503	USSR	PAYLAOD	1400	19-Oct-68	1-Nov-68	545	475	62.2	DELIBERATE	DEBRIS IMPACT
19	METEOR 1-1 R/B	1969-029B	3836	USSR	ROCKET BODY	1440	26-Mar-69	28-Mar-69	850	460	81.2	UNKNOWN	VOSTOK FINAL STAGE
20	INTELSAT 3 F-5 R/B	1969-064B	4052	USA	ROCKET BODY	1100	26-Jul-69	26-Jul-69	5445	270	30.4	PROPULSION	TE 364-4 STAGE
21	OPS 7613 R/B	1969-082AB	4159	USA	ROCKET BODY	600	30-Sep-69	4-Oct-69	940	905	70.0	UNKNOWN	AGENA D STAGE
22	NIMBUS 4 R/B	1970-025C	4367	USA	ROCKET BODY	600	8-Apr-70	17-Oct-70	1085	1065	99.9	UNKNOWN	AGENA D STAGE
23	COSMOS 374	1970-089A	4594	USSR	PAYLOAD	1400	23-Oct-70	23-Oct-70	2130	530	62.9	DELIBERATE	SELF-DESTRUCT
24	COSMOS 375	1970-091A	4598	USSR	PAYLOAD	1400	30-Oct-70	30-Oct-70	2100	525	62.8	DELIBERATE	SELF-DESTRUCT
25	COSMOS 397	1971-015A	4964	USSR	PAYLOAD	1400	25-Feb-71	25-Feb-71	2200	575	65.8	DELIBERATE	SELF-DESTRUCT
26	COSMOS 462	1971-106A	5646	USSR	PAYLOAD	1400	3-Dec-71	3-Dec-71	1800	230	65.7	DELIBERATE	SELF-DESTRUCT
27	SALYUT 2 R/B	1973-017B	6399	USSR	ROCKET BODY	4000	3-Apr-73	3-Apr-73	245	195	51.5	PROPULSION	PROTON-K THIRD STAGE

Table 1. All Known Breakups (continued)

EVENT NO.	SATELLITE NAME	INTERNATIONAL DESIGNATOR	US SATELLITE NUMBER	SATELLITE OWNER	SATELLITE TYPE	SATELLITE MASS (KG)	LAUNCH DATE	BREAKUP DATE	APOGEE (KM)	PERIGEE (KM)	INCLINATION (DEG)	ASSESSED CAUSE	ADDITIONAL INFORMATION
28	COSMOS 554	1973-021A	6432	USSR	PAYLOAD	6300	19-Apr-73	6-May-73	350	170	72.9	DELIBERATE	SELF-DESTRUCT
29	NOAA 3 R/B	1973-086B	6921	USA	ROCKET BODY	840	6-Nov-73	28-Dec-73	1510	1500	102.1	PROPULSION	DELTA SECOND STAGE
30	COSMOS 699	1974-103A	7587	USSR	PAYLOAD	3000	24-Dec-74	17-Apr-75	445	425	65.0	UNKNOWN	COSMOS 699 CLASS
31	LANDSAT 1 R/B	1972-058B	6127	USA	ROCKET BODY	800	23-Jul-72	22-May-75	910	635	98.3	PROPULSION	DELTA SECOND STAGE
32	PAGEOS	1966-056A	2253	USA	PAYLOAD	55	24-Jun-66	12-Jul-75	5170	3200	85.3	UNKNOWN	INFLATABLE SPHERE
33	NOAA 4 R/B	1974-089D	7532	USA	ROCKET BODY	900	15-Nov-74	20-Aug-75	1460	1445	101.7	PROPULSION	DELTA SECOND STAGE
34	COSMOS 758	1975-080A	8191	USSR	PAYLOAD	5700	5-Sep-75	6-Sep-75	325	175	67.1	DELIBERATE	SELF-DESTRUCT
35	COSMOS 777	1975-102A	8416	USSR	PAYLOAD	3000	29-Oct-75	25-Jan-76	440	430	65.0	UNKNOWN	COSMOS 699 CLASS
36	LANDSAT 2 R/B	1975-004B	7616	USA	ROCKET BODY	900	22-Jan-75	9-Feb-76	915	740	97.8	PROPULSION	DELTA SECOND STAGE
37	COSMOS 844	1976-072A	9046	USSR	PAYLOAD	5700	22-Jul-76	25-Jul-76	355	170	67.1	DELIBERATE	SELF-DESTRUCT
38	COSMOS 886	1976-126A	9634	USSR	PAYLOAD	1400	27-Dec-76	27-Dec-76	2295	595	65.8	DELIBERATE	SELF-DESTRUCT
39	COSMOS 884	1976-123A	9614	USSR	PAYLOAD	6300	17-Dec-76	29-Dec-76	320	170	65.0	DELIBERATE	SELF-DESTRUCT
40	COSMOS 862	1976-105A	9495	USSR	PAYLOAD	1250	22-Oct-76	15-Mar-77	39645	765	63.2	DELIBERATE	SELF-DESTRUCT
41	COSMOS 838	1976-063A	8932	USSR	PAYLOAD	3000	2-Jul-76	17-May-77	445	415	65.1	UNKNOWN	COSMOS 699 CLASS
42	HIMAWARI 1 R/B	1977-065B	10144	USA	ROCKET BODY	900	14-Jul-77	14-Jul-77	2025	535	29.0	PROPULSION	DELTA SECOND STAGE
43	COSMOS 839	1976-067A	9011	USSR	PAYLOAD	650	8-Jul-76	29-Sep-77	2100	980	65.9	BATTERY	
44	COSMOS 931	1977-068A	10150	USSR	PAYLOAD	1250	20-Jul-77	24-Oct-77	39665	680	62.9	DELIBERATE	SELF-DESTRUCT
45	COSMOS 970	1977-121A	10531	USSR	PAYLOAD	1400	21-Dec-77	21-Dec-77	1140	945	65.8	DELIBERATE	SELF-DESTRUCT
46	NOAA 5 R/B	1976-077B	9063	USA	ROCKET BODY	900	29-Jul-76	24-Dec-77	1520	1505	102.0	PROPULSION	DELTA SECOND STAGE
47	COSMOS 903	1977-027A	9911	USSR	PAYLOAD	1250	11-Apr-77	8-Jun-78	39035	1325	63.2	DELIBERATE	SELF-DESTRUCT
48	EKRAN 2	1977-092A	10365	USSR	PAYLOAD	1750	20-Sep-77	25-Jun-78	35800	35785	0.1	BATTERY	
49	COSMOS 1030	1978-083A	11015	USSR	PAYLOAD	1250	6-Sep-78	10-Oct-78	39760	665	62.8	DELIBERATE	SELF-DESTRUCT
50	COSMOS 880	1976-120A	9601	USSR	PAYLOAD	650	9-Dec-76	27-Nov-78	620	550	65.8	BATTERY	
51	COSMOS 917	1977-047A	10059	USSR	PAYLOAD	1250	16-Jun-77	30-Mar-79	38725	1645	62.9	DELIBERATE	SELF-DESTRUCT
52	COSMOS 1124	1979-077A	11509	USSR	PAYLOAD	1250	28-Aug-79	9-Sep-79	39795	570	63.0	DELIBERATE	SELF-DESTRUCT
53	COSMOS 1094	1979-033A	11333	USSR	PAYLOAD	3000	18-Apr-79	17-Sep-79	405	380	65.0	UNKNOWN	COSMOS 699 CLASS
54	COSMOS 1109	1979-058A	11417	USSR	PAYLOAD	1250	27-Jun-79	Feb-80	39425	960	63.3	DELIBERATE	SELF-DESTRUCT
55	CAT R/B	1979-104B	11659	ESA	ROCKET BODY	1400	24-Dec-79	Apr-80	33140	180	17.9	UNKNOWN	ARIANE 1 FINAL STAGE
56	COSMOS 1174	1980-030A	11765	USSR	PAYLOAD	1400	18-Apr-80	18-Apr-80	1660	380	66.1	DELIBERATE	SELF-DESTRUCT
57	LANDSAT 3 R/B	1978-026C	10704	USA	ROCKET BODY	900	5-Mar-78	27-Jan-81	910	900	98.8	PROPULSION	DELTA SECOND STAGE
58	COSMOS 1261	1981-031A	12376	USSR	PAYLOAD	1250	31-Mar-81	Apr-81	39765	610	63.0	DELIBERATE	SELF-DESTRUCT
59	COSMOS 1191	1980-057A	11871	USSR	PAYLOAD	1250	2-Jul-80	14-May-81	39255	1110	62.6	DELIBERATE	SELF-DESTRUCT

Table 1. All Known Breakups (continued)

EVENT NO.	SATELLITE NAME	INTERNATIONAL DESIGNATOR	US SATELLITE NUMBER	SATELLITE OWNER	SATELLITE TYPE	SATELLITE MASS (KG)	LAUNCH DATE	BREAKUP DATE	APOGEE (KM)	PERIGEE (KM)	INCLINATION (DEG)	ASSESSED CAUSE	ADDITIONAL INFORMATION
60	COSMOS 1167	1980-021A	11729	USSR	PAYLOAD	3000	14-Mar-80	15-Jul-81	450	355	65.0	UNKNOWN	COSMOS 699 CLASS
61	COSMOS 1275	1981-053A	12504	USSR	PAYLOAD	800	4-Jun-81	24-Jul-81	1015	960	83.0	BATTERY	
62	COSMOS 1305 R/B	1981-088F	12827	USSR	ROCKET BODY	1100	11-Sep-81	11-Sep-81	13795	605	62.8	PROPULSION	MOLNIYA FINAL STAGE
63	COSMOS 1247	1981-016A	12303	USSR	PAYLOAD	1250	19-Feb-81	20-Oct-81	39390	970	63.0	DELIBERATE	SELF-DESTRUCT
64	COSMOS 1285	1981-071A	12627	USSR	PAYLOAD	1250	4-Aug-81	21-Nov-81	40100	720	63.1	DELIBERATE	SELF-DESTRUCT
65	NIMBUS 7 R/B	1978-098B	11081	USA	ROCKET BODY	900	24-Oct-78	26-Dec-81	955	935	99.3	UNKNOWN	DELTA SECOND STAGE
66	COSMOS 1260	1981-028A	12364	USSR	PAYLOAD	3000	20-Mar-81	8-May-82	750	450	65.0	UNKNOWN	COSMOS 699 CLASS
67	COSMOS 1220	1980-089A	12054	USSR	PAYLOAD	3000	4-Nov-80	20-Jun-82	885	570	65.0	UNKNOWN	COSMOS 699 CLASS
68	COSMOS 1306	1981-089A	12828	USSR	PAYLOAD	3000	14-Sep-81	12-Jul-82	405	380	64.9	UNKNOWN	COSMOS 699 CLASS
69	COSMOS 1286	1981-072A	12631	USSR	PAYLOAD	3000	4-Aug-81	29-Sep-82	325	300	65.0	UNKNOWN	COSMOS 699 CLASS
70	COSMOS 1423 R/B	1982-115E	13696	USSR	ROCKET BODY	1100	8-Dec-82	8-Dec-82	425	235	62.9	PROPULSION	MOLNIYA FINAL STAGE
71	COSMOS 1217	1980-085A	12032	USSR	PAYLOAD	1250	24-Oct-80	12-Feb-83	38830	1530	65.2	DELIBERATE	SELF-DESTRUCT
72	COSMOS 1481	1983-070A	14182	USSR	PAYLOAD	1250	8-Jul-83	9-Jul-83	39225	625	62.9	DELIBERATE	SELF-DESTRUCT
73	COSMOS 1355	1982-038A	13150	USSR	PAYLOAD	3000	29-Apr-82	8-Aug-83	395	360	65.1	UNKNOWN	COSMOS 699 CLASS
74	COSMOS 1456	1983-038A	14034	USSR	PAYLOAD	1250	25-Apr-83	13-Aug-83	39630	730	63.3	DELIBERATE	SELF-DESTRUCT
75	COSMOS 1405	1982-088A	13508	USSR	PAYLOAD	3000	4-Sep-82	20-Dec-83	340	310	65.0	UNKNOWN	COSMOS 699 CLASS
76	COSMOS 1317	1981-108A	12933	USSR	PAYLOAD	1250	31-Oct-81	25-28 Jan-84	39055	1315	62.8	DELIBERATE	SELF-DESTRUCT
77	WESTAR 6 R/B	1984-011F	14694	USA	ROCKET BODY	2200	3-Feb-84	3-Feb-84	310	305	28.5	PROPULSION	PAM-D UPPER STAGE
78	PALAPA B2 R/B	1984-011E	14693	USA	ROCKET BODY	2200	3-Feb-84	6-Feb-84	285	275	28.5	PROPULSION	PAM-D UPPER STAGE
79	ASTRON ULLAGE MOTOR	1983-020B	13902	USSR	OP. DEBRIS	55	23-Mar-83	3-Sep-84	1230	220	51.5	PROPULSION	PROTON-K BLOCK DM SOZ
80	COSMOS 1461	1983-044A	14064	USSR	PAYLOAD	3000	7-May-83	11-Mar-85	890	570	65.0	UNKNOWN	COSMOS 699 CLASS
81	COSMOS 1654	1985-039A	15734	USSR	PAYLOAD	5700	23-May-85	21-Jun-85	300	185	64.9	DELIBERATE	SELF-DESTRUCT
82	P-78/SOLWIND	1979-017A	11278	USA	PAYLOAD	850	24-Feb-79	13-Sep-85	545	515	97.6	DELIBERATE	HYPERVELOCITY IMPACT
83	COSMOS 1375	1982-055A	13259	USSR	PAYLOAD	650	6-Jun-82	21-Oct-85	1000	990	65.8	BATTERY	
84	COSMOS 1691 (1695)	1985-094B	16139	USSR	PAYLOAD	220	9-Oct-85	22-Nov-85	1415	1410	82.6	BATTERY	
85	COSMOS 1714 R/B	1985-121F	16439	USSR	ROCKET BODY	9000	28-Dec-85	28-Dec-85	830	165	71.0	PROPULSION	ZENIT SECOND STAGE
86	NOAA 8	1983-022A	13923	USA	PAYLOAD	1000	28-Mar-83	30-Dec-85	830	805	98.6	BATTERY	
87	COSMOS 1588	1984-083A	15167	USSR	PAYLOAD	3000	7-Aug-84	23-Feb-86	440	410	65.0	UNKNOWN	COSMOS 699 CLASS
88	USA 19	1986-069A	16937	USA	PAYLOAD	930	5-Sep-86	5-Sep-86	745	210	39.1	DELIBERATE	HYPERVELOCITY IMPACT
89	USA 19 R/B	1986-069B	16938	USA	ROCKET BODY	1455	5-Sep-86	5-Sep-86	610	220	22.8	DELIBERATE	HYPERVELOCITY IMPACT
90	SPOT 1 R/B	1986-019C	16615	ESA	ROCKET BODY	1400	22-Feb-86	13-Nov-86	835	805	98.7	UNKNOWN	ARIANE 1 FINAL STAGE
91	COSMOS 1278	1981-058A	12547	USSR	PAYLOAD	1250	19-Jun-81	Dec-86	37690	2665	67.1	DELIBERATE	SELF-DESTRUCT

Table 1. All Known Breakups (continued)

EVENT NO.	SATELLITE NAME	INTERNATIONAL DESIGNATOR	US SATELLITE NUMBER	SATELLITE OWNER	SATELLITE TYPE	SATELLITE MASS (KG)	LAUNCH DATE	BREAKUP DATE	APOGEE (KM)	PERIGEE (KM)	INCLINATION (DEG)	ASSESSED CAUSE	ADDITIONAL INFORMATION
92	COSMOS 1682	1985-082A	16054	USSR	PAYLOAD	3000	19-Sep-85	18-Dec-86	475	385	65.0	UNKNOWN	COSMOS 699 CLASS
93	COSMOS 1813	1987-004A	17297	USSR	PAYLOAD	6300	15-Jan-87	29-Jan-87	415	360	72.8	DELIBERATE	SELF-DESTRUCT
94	COSMOS 1866	1987-059A	18184	USSR	PAYLOAD	5700	9-Jul-87	26-Jul-87	255	155	67.1	DELIBERATE	SELF-DESTRUCT
95	AUSSAT K3/ECS 4 R/B	1987-078C	18352	ESA	ROCKET BODY	1200	16-Sep-87	16-19 Sep-87	36515	245	6.9	UNKNOWN	ARIANE 3 FINAL STAGE
96	COSMOS 1769	1986-059A	16895	USSR	PAYLOAD	3000	4-Aug-86	21-Sep-87	445	310	65.0	UNKNOWN	COSMOS 699 CLASS
97	COSMOS 1646	1985-030A	15653	USSR	PAYLOAD	3000	18-Apr-85	20-Nov-87	410	385	65.0	UNKNOWN	COSMOS 699 CLASS
98	COSMOS 1823	1987-020A	17535	USSR	PAYLOAD	1500	20-Feb-87	17-Dec-87	1525	1480	73.6	BATTERY	
99	COSMOS 1656 ULLAGE MOTOR	1985-042E	15773	USSR	OP. DEBRIS	55	30-May-85	5-Jan-88	860	810	66.6	PROPULSION	PROTON-K BLOCK DM SOZ
100	COSMOS 1906	1987-108A	18713	USSR	PAYLOAD	6300	26-Dec-87	31-Jan-88	265	245	82.6	DELIBERATE	SELF-DESTRUCT
101	COSMOS 1916	1988-007A	18823	USSR	PAYLOAD	5700	3-Feb-88	27-Feb-88	230	150	64.8	DELIBERATE	SELF-DESTRUCT
102	COSMOS 1045 R/B	1978-100D	11087	USSR	ROCKET BODY	1360	26-Oct-78	9-May-88	1705	1685	82.6	UNKNOWN	TSYKLON THIRD STAGE
103	COSMOS 2030	1989-054A	20124	USSR	PAYLOAD	5700	12-Jul-89	28-Jul-89	215	150	67.1	DELIBERATE	SELF-DESTRUCT
104	COSMOS 2031	1989-056A	20136	USSR	PAYLOAD	6000	18-Jul-89	31-Aug-89	365	240	50.5	DELIBERATE	SELF-DESTRUCT
105	FENGYUN 1-2 R/B	1990-081D	20791	PRC	ROCKET BODY	1000	3-Sep-90	4-Oct-90	895	880	98.9	PROPULSION	CZ-4A FINAL STAGE
106	COSMOS 2101	1990-087A	20828	USSR	PAYLOAD	6000	1-Oct-90	30-Nov-90	280	195	64.8	DELIBERATE	SELF-DESTRUCT
107	USA 68	1990-105A	20978	USA	PAYLOAD	855	1-Dec-90	1-Dec-90	850	610	98.9	PROPULSION	TE-M-364-15 UPPER STAGE
108	COSMOS 1519-21 ULLAGE MOTOR	1983-127H	14608	USSR	OP. DEBRIS	55	29-Dec-83	4-Feb-91	18805	340	51.9	PROPULSION	PROTON-K BLOCK DM SOZ
109	COSMOS 2125-32 R/B	1991-009J	21108	USSR	ROCKET BODY	1435	12-Feb-91	5-Mar-91	1725	1460	74.0	PROPULSION	COSMOS SECOND STAGE
110	NIMBUS 6 R/B	1975-052B	7946	USA	ROCKET BODY	900	12-Jun-75	1-May-91	1105	1095	99.6	PROPULSION	DELTA SECOND STAGE
111	COSMOS 2163	1991-071A	21741	USSR	PAYLOAD	6000	9-Oct-91	6-Dec-91	260	185	64.8	DELIBERATE	SELF-DESTRUCT
112	COSMOS 1710-12 ULLAGE MOTOR	1985-118L	16446	USSR	OP. DEBRIS	55	24-Dec-85	29-Dec-91	18885	655	65.3	PROPULSION	PROTON-K BLOCK DM SOZ
113	OV2-5 R/B	1968-081E	3432	USA	ROCKET BODY	2555	26-Sep-68	21-Feb-92	35810	35100	11.9	UNKNOWN	TITAN TRANSTAGE
114	COSMOS 2054 ULLAGE MOTOR	1989-101E	20399	USSR	OP. DEBRIS	55	27-Dec-89	Jul-92	27650	345	47.1	PROPULSION	PROTON-K BLOCK DM SOZ
115	COSMOS 1603 ULLAGE MOTOR	1984-106F	15338	USSR	OP. DEBRIS	55	28-Sep-84	5-Sep-92	845	835	66.6	PROPULSION	PROTON-K BLOCK DM SOZ
116	GORIZONT 17 ULLAGE MOTOR	1989-004E	19771	USSR	OP. DEBRIS	55	26-Jan-89	17-Dec-92	17575	195	46.7	PROPULSION	PROTON-K BLOCK DM SOZ
117	COSMOS 2227 R/B	1992-093B	22285	RF	ROCKET BODY	9000	25-Dec-92	26-Dec-92	855	845	71.0	PROPULSION	ZENIT-2 SECOND STAGE
118	GORIZONT 18 ULLAGE MOTOR	1989-052F	20116	USSR	OP. DEBRIS	55	5-Jul-89	12-Jan-93	36745	260	46.8	PROPULSION	PROTON-K BLOCK DM SOZ
119	COSMOS 2225	1992-091A	22280	RF	PAYLOAD	6000	22-Dec-92	18-Feb-93	280	225	64.9	DELIBERATE	SELF-DESTRUCT
120	COSMOS 2237 R/B	1993-016B	22566	RF	ROCKET BODY	9000	26-Mar-93	28-Mar-93	850	840	71.0	PROPULSION	ZENIT-2 SECOND STAGE
121	TELECOM 2B/INMARSAT 2 R/B	1992-021C	21941	ESA	ROCKET BODY	1800	15-Apr-92	21-Apr-93	34080	235	4.0	UNKNOWN	ARIANE 4 H10+ FINAL STAGE
122	COSMOS 2243	1993-028A	22641	RF	PAYLOAD	5700	27-Apr-93	27-Apr-93	225	180	70.4	DELIBERATE	SELF-DESTRUCT
123	COSMOS 2259	1993-045A	22716	RF	PAYLOAD	5700	14-Jul-93	25-Jul-93	320	175	67.1	DELIBERATE	SELF-DESTRUCT

Table 1. All Known Breakups (continued)

EVENT NO.	SATELLITE NAME	INTERNATIONAL DESIGNATOR	US SATELLITE NUMBER	SATELLITE OWNER	SATELLITE TYPE	SATELLITE MASS (KG)	LAUNCH DATE	BREAKUP DATE	APOGEE (KM)	PERIGEE (KM)	INCLINATION (DEG)	ASSESSED CAUSE	ADDITIONAL INFORMATION
124	COSMOS 1484	1983-075A	14207	USSR	PAYLOAD	1800	24-Jul-83	18-Oct-93	595	550	97.5	UNKNOWN	
125	COSMOS 2262	1993-057A	22789	RF	PAYLOAD	6000	7-Sep-93	18-Dec-93	295	170	64.9	DELIBERATE	SELF-DESTRUCT
126	CLEMENTINE R/B	1994-004B	22974	USA	ROCKET BODY	2860	25-Jan-94	7-Feb-94	295	240	67.0	UNKNOWN	
127	OPS 9331-34 R/B	1967-066G	2868	USA	ROCKET BODY	2555	1-Jul-67	8-Feb-94	33675	33250	11.7	UNKNOWN	TITAN TRANSTAGE
128	ASTRA 1B/MOP 2 R/B	1991-015C	21141	ESA	ROCKET BODY	1760	2-Mar-91	27-Apr-94	17630	205	6.8	UNKNOWN	ARIANE 4 H10 FINAL STAGE
129	COSMOS 2133 ULLAGE MOTOR	1991-010D	21114	USSR	OP. DEBRIS	55	12-Feb-91	7-May-94	21805	225	46.6	PROPULSION	PROTON-K BLOCK DM SOZ
130	COSMOS 2204-06 ULLAGE MOTOR	1992-047H	22067	RF	OP. DEBRIS	55	30-Jul-92	8-Nov-94	19035	480	64.8	PROPULSION	PROTON-K BLOCK DM SOZ
131	RS-15 R/B	1994-085B	23440	RF	ROCKET BODY	3100	26-Dec-94	26-Dec-94	2200	1880	64.8	UNKNOWN	ROKOT THIRD STAGE
132	ETS-VI R/B	1994-056B	23231	JAPAN	ROCKET BODY	3000	28-Aug-94	31-Mar-95	4840	100	28.6	AERODYNAMICS	H-II SECOND STAGE
133	ELEKTRO ULLAGE MOTOR	1994-069E	23338	RF	OP. DEBRIS	55	31-Oct-94	11-May-95	35465	155	46.9	PROPULSION	PROTON-K BLOCK DM SOZ
134	COSMOS 2282 ULLAGE MOTOR	1994-038F	23174	RF	OP. DEBRIS	55	6-Jul-94	21-Oct-95	34930	280	47.0	PROPULSION	PROTON-K BLOCK DM SOZ
135	GORIZONT 22 ULLAGE MOTOR	1990-102E	20957	USSR	OP. DEBRIS	55	23-Nov-90	14-Dec-95	13105	170	46.5	PROPULSION	PROTON-K BLOCK DM SOZ
136	RADUGA 33 R/B	1996-010D	23797	RF	ROCKET BODY	2600	19-Feb-96	19-Feb-96	36505	240	48.7	PROPULSION	PROTON-K BLOCK DM
137	ITALSAT 1/EUTELSAT 2 F2 R/B	1991-003C	21057	ESA	ROCKET BODY	1760	15-Jan-91	Apr/May 96	30930	235	6.7	UNKNOWN	ARIANE 4 H10 FINAL STAGE
138	STEP II R/B	1994-029B	23106	USA	ROCKET BODY	97	19-May-94	3-Jun-96	820	585	82.0	PROPULSION	PEGASUS HAPS
139	CERISE	1995-033B	23606	FRANCE	PAYLOAD	50	7-Jul-95	24-Jul-96	675	665	98.1	COLLISION	
140	COSMOS 1883-85 ULLAGE MOTOR	1987-079G	18374	USSR	OP. DEBRIS	55	16-Sep-87	1-Dec-96	19120	335	64.9	PROPULSION	PROTON-K BLOCK DM SOZ
141	EKRAN 17 ULLAGE MOTOR	1987-109E	18719	USSR	OP. DEBRIS	55	27-Dec-87	22-May-97	22975	310	46.6	PROPULSION	PROTON-K BLOCK DM SOZ
142	COSMOS 2313	1995-028A	23596	RF	PAYLOAD	3000	8-Jun-95	26-Jun-97	325	210	65.0	UNKNOWN	COSMOS 699 CLASS
143	COSMOS 2343	1997-024A	24805	RF	PAYLOAD	6000	15-May-97	16-Sep-97	285	225	65.0	DELIBERATE	SELF-DESTRUCT
144	COSMOS 1869	1987-062A	18214	RF	PAYLOAD	1900	16-Jul-87	27-Nov-97	635	605	83.0	UNKNOWN	
145	COSMOS 1172	1980-028A	11758	USSR	PAYLOAD	1250	12-Apr-80	23-Dec-97	5125	75	61.8	AERODYNAMICS	
146	ASIASAT 3 R/B	1997-086D	25129	RF	ROCKET BODY	2600	24-Dec-97	25-Dec-97	35995	270	51.0	PROPULSION	PROTON-K BLOCK DM
147	MOLNIYA 3-16	1981-054A	12512	USSR	PAYLOAD	1600	9-Jun-81	5-Feb-98	7670	85	62.1	AERODYNAMICS	
148	ELEKTRON 1/2 R/B	1964-006D	751	USSR	ROCKET BODY	1440	30-Jan-64	13-Feb-98	56315	90	56.2	AERODYNAMICS	VOSTOK FINAL STAGE
149	METEOR 2-16 R/B	1987-068B	18313	USSR	ROCKET BODY	1360	18-Aug-87	15-Feb-98	960	940	82.6	UNKNOWN	TSYKLON THIRD STAGE
150	SKYNET 4B/ASTRA 1A R/B	1988-109C	19689	ESA	ROCKET BODY	1760	11-Dec-88	17-Feb-98	35875	435	7.3	UNKNOWN	ARIANE 4 H10 FINAL STAGE
151	COMETS R/B	1998-011B	25176	JAPAN	ROCKET BODY	3000	21-Feb-98	21-Feb-98	1880	245	30.0	PROPULSION	H-II SECOND STAGE
152	COSMOS 2109-11 ULLAGE MOTOR	1990-110H	21013	USSR	OP. DEBRIS	55	8-Dec-90	14-Mar-98	18995	520	65.1	PROPULSION	PROTON-K BLOCK DM SOZ
153	COSMOS 1987-89 ULLAGE MOTOR	1989-001G	19755	USSR	OP. DEBRIS	55	10-Jan-89	3-Aug-98	19055	340	64.9	PROPULSION	PROTON-K BLOCK DM SOZ

Table 2. Satellite Anomalous Events (continued)

EVENT NO.	SATELLITE NAME	INTERNATIONAL DESIGNATOR	US SATELLITE NUMBER	LAUNCH DATE	FIRST EVENT DATE	KNOWN EVENTS	APOGEE (KM)	PERIGEE (KM)	INCLINATION (DEG)
1	GEOS 3 R/B	1975-027B	7735	9-Apr-75	Mar-78	1	845	835	115.0
2	OPS 4682 (SNAPSHOT)	1965-027A	1314	3-Apr-65	1-Nov-79	7	1320	1270	90.3
3	OPS 1593 (TRANSIT 11)	1966-005A	1952	28-Jan-66	Apr-80	4	1205	855	89.8
4	OPS 8480 (TRANSIT 5B-6)	1965-048A	1420	24-Jun-65	Aug-80	4	1135	1025	89.9
5	OPS 4988 (GREB 6)	1965-016A	1271	9-Mar-65	Nov-80	1	935	900	70.1
6	OPS 4412 (TRANSIT 9)	1964-026A	801	4-Jun-64	Dec-80	4	930	845	90.5
7	OPS 4947 (TRANSIT 17)	1967-092A	2965	25-Sep-67	Apr-81	4	1110	1035	89.3
8	NIMBUS 7 R/B	1978-098B	11081	24-Oct-78	May-81	2	955	935	99.3
9	OPS 1117 (TRANSIT 12)	1966-024A	2119	26-Mar-66	Jul-81	1	1115	890	89.9
10	SEASAT	1978-064A	10967	27-Jun-78	Jul-83	2	780	780	108.0
11	OSCAR 24/30	1985-066A/B	15935/6	3-Aug-85	Nov-86	2	1255	1000	89.9
12	METEOR 1-7 R/B	1971-003B	4850	20-Jan-71	Jun-87	1	665	535	81.2
13	TIROS-N	1978-096A	11060	13-Oct-78	Sep-87	2	855	835	99.0
14	KYOKKOH 1 (EXOS-A)	1978-014A	10664	4-Feb-78	Jan-88	2	4220	760	65.0
15	METEOR 1-12 R/B	1972-049B	6080	30-Jun-72	Sep-89	1	935	860	81.2
16	COSMOS 44 R/B	1964-053B	877	28-Aug-64	Nov-90	1	775	655	65.1
17	COSMOS 206 R/B	1968-019B	3151	14-Mar-68	Nov-90	1	515	450	81.2
18	OPS 0856	1966-077A	2403	19-Aug-66	Mar-91	5	3710	3660	89.7
19	OPS 0100 (TRANSIT 15)	1967-034A	2754	14-Apr-67	Sep-92	1	1065	1035	90.1
20	COSMOS 1043	1978-094A	11055	10-Oct-78	Feb-93	1	435	435	81.2
21	COBE	1989-089A	20322	18-Nov-89	Mar-93	12	885	870	99.0
22	NOAA 7	1981-059A	12553	23-Jun-81	26-Jul-93	2	835	830	98.9
23	OPS 7218 (TRANSIT 16)	1967-048A	2807	18-May-67	Feb-95	1	1090	1060	89.6
24	NOAA 6	1979-057A	11416	27-Jun-79	Jun-95	1	810	795	98.7
25	KOREASAT 1 R/B	1995-041B	23640	5-Aug-95	6-Dec-95	1	1375	935	26.7
26	RADARSAT R/B	1995-059B	23711	4-Nov-95	30-Jan-96	1	1495	935	100.6
27	COSMOS 1939 R/B	1988-032B	19046	20-Apr-88	30-Jul-96	2	655	585	97.6
28	METEOR 2-7 R/B	1981-043B	12457	14-May-81	Oct-96	1	920	825	81.3
29	OPS 1509 (TRANSIT 10)	1965-109A	1864	22-Dec-65	30-Nov-96	2	1065	895	89.1
30	TRANSIT 5B-2	1963-049B	704	5-Dec-63	9/10-Jan-98	1	1110	1060	90.1
31	NIMBUS 2	1966-040A	2173	15-May-66	Nov-97	1	1175	1095	100.4
32	EKA 1 (START 1)	1993-014A	22561	25-Mar-93	4-Mar-98	1	970	685	75.8
33	TRANSIT 19	1970-067A	4507	27-Aug-70	7-Mar-98	1	1205	945	90.0

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