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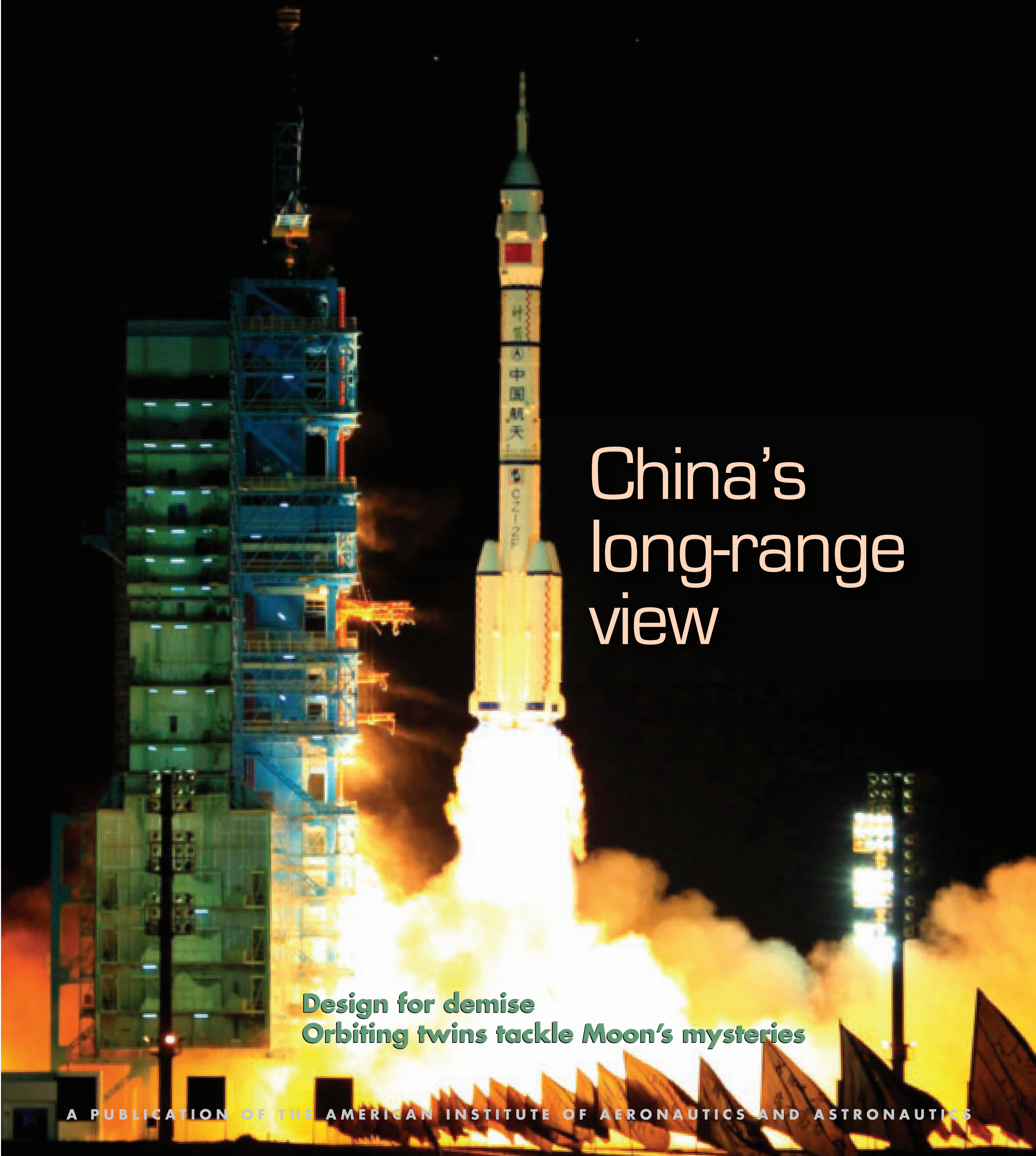

China's long-range view

Design for demise

Orbiting twins tackle Moon's mysteries

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Design for *demise*

Protection from falling spacecraft

The probability that falling spacecraft could do harm on Earth is very low, but it is not negligible. The risk will only increase as more satellites reach the end of their lives and reenter Earth's atmosphere. To minimize danger to populated areas, NASA is calling for spacecraft components to be designed not to survive reentry.

The heavens deliver tens of tons of man-made refuse into the Earth's atmosphere each year. While there is a very low probability that a bystander on terra firma will suffer injury from falling space clutter, the risk cannot be disregarded.

Last year brought several reminders that uncontrolled reentries of spacecraft, possibly over populated areas, can produce public consternation and stir an uptick in media coverage.

In 1995 NASA established a human ca-

The GPM satellite was designed from the beginning with its end in mind.

sualty risk threshold of 1 in 10,000 per reentry event for its spacecraft, booster stages, and related hardware. That risk threshold has been adopted by the U.S. government and other leading space agencies.

But it turns out that breaking up is hard to do—specifically in the case of spacecraft and launch vehicle orbital stages. Components that have high melting temperatures—titanium, stainless steel, and beryllium, for example—have been found to 'beat the heat' of reentry and could pose a danger to people on Earth. Surviving objects that commonly make it through reentry have included propellant and pressurant tanks, pieces of solar array drive mechanisms, and elements of reaction wheel assemblies.

Stepping up to this challenge is a NASA program called 'design for demise,' or D4D.

'Demisable' hydrazine tank

A plan of action now under way as an iterative process brings two worlds into collision: satellite designers and reentry survival assessment specialists. The plan urges a push toward new practices for designing space vehicles—practices that take into account reentry hazards from the very start.

by Leonard David
Contributing writer

"This is the right thing to be doing," says Nicholas Johnson, chief scientist for orbital debris at NASA Johnson in Houston. "We certainly hope to use design for demise on future NASA missions, and we're trying to get the word out to other folks," he tells *Aerospace America*.

An example is the joint mission of the global precipitation measurement (GPM) spacecraft, to be launched by NASA, JAXA, and other international partners in 2014. The craft will set new worldwide standards for precipitation measurements, a key climate factor, using a network of satellites united by the GPM core observatory.

But an issue for GPM cropped up in 2002. An analysis had identified the spacecraft's titanium tank—to be topped off with more than 500 kg of hydrazine—as a significant reentry risk. Thanks to a NASA-sponsored effort, a flight-qualified equal-capacity aluminum tank and an all-aluminum internal propellant management device were successfully fabricated. This reduced the reentry risk for the tank to zero, and also saved weight in the tank.

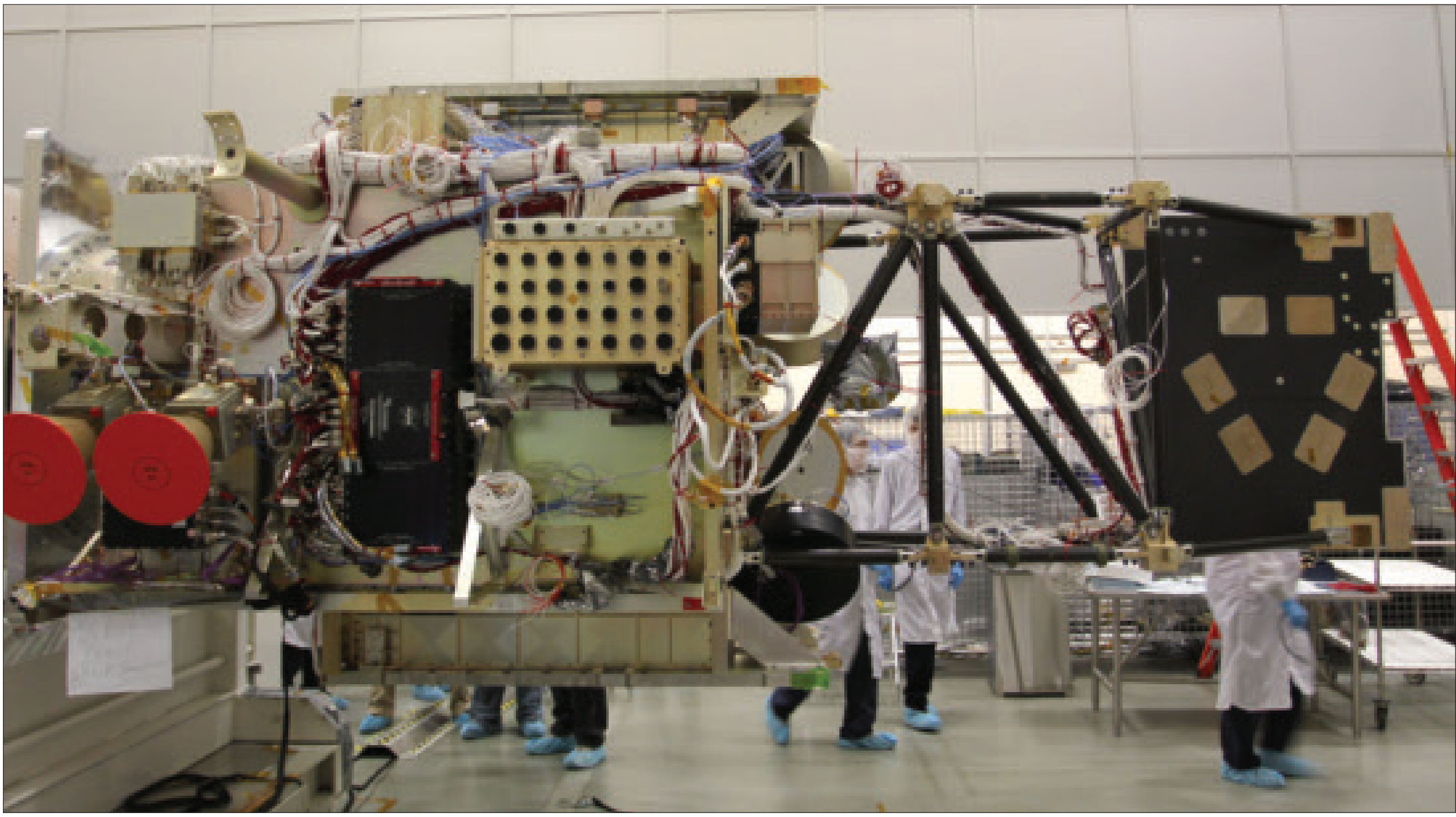
"NASA did invest a modest amount of resources into the design and development of this 'demisable' hydrazine tank," says Johnson. "Hydrazine tanks are one of the problems that we run into routinely. We did it for GPM understanding that this is an investment that will pay dividends for future missions."

Threshold guidelines

Along with the hydrazine tank changes for GPM, the satellite's solar array panels were crafted with demisability in mind. So too was the spacecraft's scientific payload: a U.S. microwave imager and a JAXA dual-frequency precipitation radar.

GPM engineers also incorporated a new reaction wheel assembly design, one that posed no risk to people on Earth. That design was adopted on NASA's lunar reconnaissance orbiter. As Johnson points out, interplanetary spacecraft that tote large hydrazine tanks are being evaluated for demisability. "We have to worry about launch malfunctions, like a Mars probe in low Earth orbit where its booster doesn't fire and it falls back to Earth."

The first set of human casualty risk threshold guidelines, issued in 1995, included a 25-year postmission disposal rule. Basically the rule requires that any future mission and its associated debris must have an orbital lifetime equal to or less than 25 years. Johnson stresses that NASA, along with other major space agencies and the U.N., agreed to this rule.



The GPM satellite, now under construction, is fitted to the bed of the high capacity centrifuge for spin testing. This spacecraft has undergone a 'design for demise' overhaul. Credit: NASA/GSFC.

"So we had to go look at this for the first time from a programmatic standpoint," says Johnson. "One of my cardinal statements is that the vast majority of objects will always survive or always demise."

A bottom line for Johnson is that in the requirements phase, NASA and vendors need to do a better job of stating what is acceptable or not acceptable. "It just takes time," he says. "This is not one of those things where you have to solve it overnight." There is an educational aspect to demise by design, a need to engage vendors who provide spacecraft buses and other satellite components.

"It's been like this for virtually all the orbital debris mitigation measures. It takes a while to educate people…to determine what's cost effective and then implement it. So we're in that process with demisability," Johnson explains.

Hot on the trail

Also hot on the trail of information on how objects respond to the severe conditions of reentry is William Ailor, director of the Center for Orbital and Reentry Debris Studies at The Aerospace Corporation in El Segundo, California.

Ailor has led development of the reentry breakup recorder (REBR), a small, autonomous device built to record temperature, acceleration, rotational rate, and other data during a spacecraft's dive to Earth. These devices have flown already, inside JAXA's Kounotori 2 H-II transfer vehicle, and in Europe's second automated transfer vehicle (ATV), the Johannes Kepler. Both vehicles took their turns at making self-destructive plunges last year after performing resupply duties at the space station.

Each REBR includes a heat shield that protects instruments and the collected data accumulated during reentry.

Years of work on the REBR have been aided by the Air Force and NASA Goddard, Ailor says. Boeing supplied the heat shields and NASA Ames provided in-kind support of the self-stabilizing heat shield design.

Microinstruments, tiny sensors, and ultrasmall cellphone technology are what made it possible to create the REBR, notes Ailor. The compact unit is basically a satellite phone with a heat shield, he says. Rather than broadcasting data during the breakup event, REBR records the data and transmits information after the reentry has effectively ended but before the data recorder actually impacts Earth.

A reentry breakup recorder includes a heat shield to protect tiny instruments that gather information on how space hardware reacts during a fiery reentry into Earth's atmosphere. Credit: The Aerospace Corporation.

'Black box' systems

The REBR assembly—including housing and interface adaptor—weighs all of 8.6 kg and is 36 cm in diameter and 28 cm long. REBR itself, the instrument package and heat shield assembly, weighs a modest 4 kg and is 30 cm in diameter and 23 cm long.

At present, REBR instrumentation includes two three-axis accelerometers; a rate gyro that captures angular rates about the three REBR axes; a sensor that measures REBR's internal pressure; a GPS receiver that captures REBR's altitude, velocity, and

UARS: Uncontrolled tumble to Earth

NASA's decommissioned Upper Atmosphere Research Satellite fell back to Earth in September. Deployed on orbit in 1991 during the STS-48 space shuttle mission, UARS was the first multiinstrumented spacecraft to observe numerous chemical components of the atmosphere to improve scientists' understanding of photochemistry.

Six years after the end of its productive scientific life, the 6.5-ton UARS broke into pieces during an uncontrolled reentry, with most of it disintegrating within the atmosphere. Twenty-six satellite components weighing a total of about 1,200 lb were assessed as possibly being able to survive the fiery reentry and strike the Earth's surface.

Prior to this uncontrolled demise, NASA explained that because the satellite's orbit was inclined 57 deg to the equator, any surviving components of UARS would land within a zone between 57 deg north latitude and 57 deg south latitude. It was impossible to pinpoint just where in that zone bits and pieces of the satellite would drop. NASA reentry experts estimated that the debris footprint would be about 500 mi. long.

As reported by the Joint Space Operations Center (JSpOC) at Vandenberg AFB in California, the satellite entered the atmosphere over the Pacific Ocean. The location was over a broad, remote ocean area in the southern hemisphere, far from any major land mass. The debris field was somewhere between 300 mi. and 800 mi. downrange, or generally northeast of the reentry point. NASA advised the public in a final post reentry statement that it was not aware of any possible debris sightings from this geographic area.

With the school-bus-sized spacecraft auguring its way through Earth's atmosphere, a number of satellite components likely made it through the fiery fall. Those may have included a high-gain antenna gimbal, fuel tanks, batteries, and reaction wheel rims. The projected surviving pieces added up to 26 components, totaling an impact mass of over 530 kg.

"This was not an easy reentry to predict because of the natural forces acting on the satellite as its orbit decayed. Spacefaring nations around the world also were monitoring the satellite's descent in the last two hours, and all the predictions were well within the range estimated by JSpOC," Johnson reports.

UTC (coordinated universal time) during its descent after release from the host vehicle; and sensors designed to capture temperatures at several locations within the REBR heat shield.

As the host vehicle reenters and breaks apart, data from these sensors are collected and recorded for several minutes. When the REBR's velocity approaches and continues to decrease below Mach 1, an Iridium modem is activated and REBR makes a call to the Iridium system to download recorded data as it falls into ocean waters. No attempts are made to recover the gear.

During last year's Japanese HTV2 reentry, says Ailor, the REBR performed well and returned data. Unfortunately, after the European ATV2's reentry, no data were received. The most likely reason for this is that the REBR was damaged during ATV2's breakup, he says, which may have presented a more severe challenge than the demise of HTV2.

According to Ailor and Michael Weaver, also of Aerospace Corporation, one way to minimize the expense of space hardware disposal is to design satellites and launch stages in a way that minimizes the possibility of survival for large, hazardous debris fragments—again, adopting a 'design for demise' philosophy.

Confidence that such design features will have the desired result requires accurate modeling of reentry breakup, and possibly a means for directly testing the breakup characteristics of candidate hardware designs. Hence, REBR offers considerable utility, with future versions perhaps serving as prototype 'black box' systems for space transportation vehicles, Ailor suggests.

Small but estimable risk

NASA Goddard is home base for building and managing a large number of missions, most of which are in Earth orbit. "We therefore have a large potential to generate, and get affected by, orbital debris. Many of those missions, particularly those in low Earth orbit, will eventually reenter the Earth's atmosphere. Although most of the

ROSAT's reentry into Bay of Bengal

Following in the reentry wake of UARS was Germany's Roentgen satellite, an astronomical X-ray observatory lofted into Earth orbit in June 1990. In its highly successful astronomy mission, the roughly 3-ton ROSAT cranked out science for nearly nine years. It was turned off in February 1999. The project was a collaborative venture by Germany, the U.S., and the U.K. and was developed, built, and launched on behalf of and under the leadership of DLR, Germany's space agency.

During the satellite's operating life, more than 4,000 scientists from 24 countries took advantage of the opportunity to request observations. Many hot, high-energy processes in the universe were first observed with ROSAT.

Like UARS, however, ROSAT did not carry a propulsion system. Thus it was not feasible to maneuver the craft into a controlled reentry at the end of its mission. Furthermore, the satellite was adrift in space, circling Earth in deaf and dumb mode. Spacecraft communications between ROSAT and DLR's control center in Oberpfaffenhofen were not possible.

An early reentry study of ROSAT indicated that nearly 2 tons of satellite leftovers could make it down and strike the Earth's surface. According to DLR, the satellite's X-ray optical system—replete with mirrors and a mechanical support structure made partly of carbon-fiber-reinforced composite—could tumble to Earth. Any of the ROSAT scraps were predicted to strike our planet at speeds reaching 280 mph.

Before ROSAT's fall, DLR noted that all areas under the dead spacecraft's orbit—which extended to 53 deg northern and southern latitude—could well be affected by its reentry. The bulk of the debris would impact near the ground/ocean track of the satellite. However, isolated fragments could descend to Earth in a 50-mi.-wide swath along that track.

DLR underscored that while the time and location of reentry could not be predicted exactly, the likelihood of ROSAT's diving into an inhabited area was exceedingly low.

On October 23, ROSAT reentered the atmosphere over the Bay of Bengal. DLR said, "It is not known whether any parts of the satellite reached Earth's surface. Determination of the time and location of reentry was based on the evaluation of data provided by international partners, including the USA."

Following the plummet of ROSAT, Johann-Dietrich Wörner, chairman of the DLR executive board, announced: "With the reentry of ROSAT, one of the most successful German scientific space missions has been brought to its ultimate conclusion. The dedication of all those involved at DLR and our national and international partners was exemplary...they are all deserving of my sincere thank-you."

Last year, the Inter-Agency Space Debris Coordination Committee (IADC) conducted an official reentry test campaign for the fall of both UARS and ROSAT. The IADC is an international governmental forum for worldwide coordination of activities and issues involving man-made and natural space debris. The purpose of these campaigns, which it has carried out since 1998, is to improve prediction accuracy via data-sharing among IADC members, particularly in the case of high-risk reentries.

NASA's Upper Atmosphere Research Satellite fell to Earth last year. During its uncontrolled reentry, the multiton satellite broke into pieces, most of which disintegrated within the atmosphere. According to an assessment, however, 26 components, weighing a total of about 1,200 lb, could have survived the fiery reentry to strike the Earth's surface. Credit: NASA.

Other targets used for past IADC reentry initiatives include Russian Cosmos satellites, various upper stages, and even the fall from space of an EAS, or early ammonia servicer—equipment purposely jettisoned from the ISS by spacewalkers in July 2007.

spacecraft components typically are expected to burn up, there are often at least a few predicted to survive reentry and reach the Earth's surface," says Scott Hull, an orbital debris engineer at Goddard.

While Earth's global commodity is water, and much of the remainder is uninhabited, Hull observes, uncontrolled reentries can still pose a small but estimable risk to the human population.

"A risk greater than 1 part in 10,000 for any reentry is considered by NASA to be unacceptable, and measures are taken to reduce that risk. One approach is to design the spacecraft so that it can perform a controlled reentry into the open ocean at the end of the mission. Another approach is to redesign some of the surviving components so that they are likely to burn up during reentry heating," he tells *Aerospace America.*

It is that other approach that was first dubbed design for demise, or D4D, by Goddard orbital debris specialists.

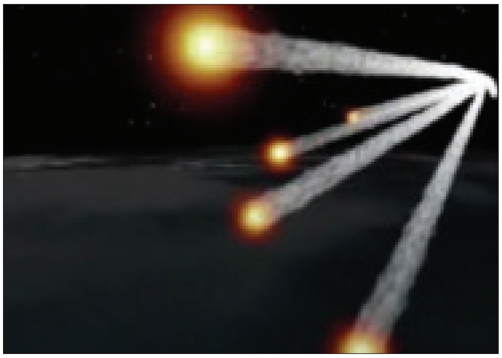
D4D involves first identifying which of the components likely to survive reentry could most reduce the reentry risk by demising instead. This could be either a very large component—say, a propulsion tank—or a large quantity of a single surviving component type. Large numbers of surviving objects have a higher likelihood of causing injury, somewhat analogous to a shotgun blast compared to a rifle bullet, says Hull, "so it is beneficial to address any objects that could survive in high quantity."

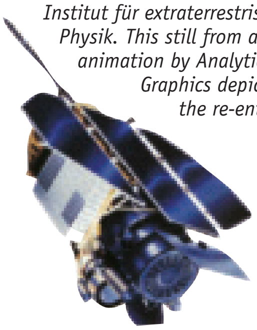
Heat of fusion

Implementing D4D involves a variety of approaches, including spacecraft material substitutions; altering the shape of a component; redesigning to use multiple smaller components; switching to a different technology; or simply bundling many small items into a single surviving object.

"One of the main drivers for determining whether a component survives reentry heating is the heat of ablation for the primary material in that component," Hull explains. "The heat of ablation is the total amount of heat required to raise the temperature of the component to its melting temperature…then overcome the heat of fusion to allow the object to actually melt."

There is a list of common spacecraft materials that can thwart high heats during the ablation process. These include titanium, stainless steel, glass, ceramics, and beryllium. On the other side of the heat load are graphite-epoxy composites, aluminum, and polymers—all generally have low heat of ablation.





Germany's ROSAT, an astronomical X-ray observatory, made its uncontrolled reentry in October 2011, tumbling through the atmosphere over the Bay of Bengal. Image credit: Max-Planck-Institut für extraterrestrische Physik. This still from an animation by Analytical Graphics depicts the re-entry.

"In consultation with component designers, it is often possible to redesign a titanium component using graphite-epoxy, for example," notes Hull. It will "retain approximately the same thermal expansion coefficient," but burn up on reentry, he says.

Last March a hiker in Moffat County, near the NW corner of Colorado, heard a high-pitched sound he could not identify. A short time later, he noticed a 30-in.-diam. object in a crater about a foot deep. The object was later identified as a spherical titanium tank from a Russian upper-stage rocket launched in January. A follow-up search found another, smaller sphere 34 mi. to the northeast. Courtesy of Elizabeth Campbell/NRC study, Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs.

"Of course, all material properties must be taken into account, since titanium may have been selected initially for its chemical properties or strength, which the new material might not meet. Aluminum can be a handy substitution material because it not only has a low heat of ablation, but also experiences generous oxidation heating/burning to generate even more heat during reentry, especially at lower altitude," Hull points out.

He says it is sometimes possible to redesign a component to a different shape that will enable it to reenter faster, thus generating more heat during reentry. "We had one support flange that was initially designed with flat legs, which presented high drag during reentry. By redesigning these supports to use square tubular legs, the component retained its strength, but was more likely to burn up while falling through the atmosphere,” Hull says.

In another case, spacecraft designers looked at balance weights that might survive and potentially injure people. “By redesigning to a cluster of very small pieces,” they made the weights “small enough that they would not cause a serious injury, even in the unlikely event that one would hit a person,” says Hull.

Cost and schedule challenges

Yet another plus in reducing the reentry risk for most new missions is the growing use of lithium-ion battery technology in spacecraft. Hull says stainless steel and Invar pressure vessels used in nickel-hydrogen batteries have often been replaced by a thin stainless steel or aluminum case, with highly demisable materials inside. While the choice of battery technology is generally a result of other factors such as power usage rates, he adds that there have been cases where the demisability of the battery was a factor in this decision.

In summing up D4D techniques, Hull stresses that there are challenges, including cost and schedule impacts. There is also the qualification of a new design.

“By employing these techniques early in the process, the cost and schedule impacts can be minimized,” Hull says. “Unfortunately, though, high survivability objects are often not noticed or added into the spacecraft design until late in the design process, when D4D is more difficult and costly to implement.”

Hull adds that that there is always reluctance to move away from a heritage design approach, even when other benefits are shown. The proven success of a design that has ‘always been done this way’ is difficult to argue with in the face of an elevated—but still very small—risk of something that might happen decades from now. “The increased reentry risk must be dealt with at design, though, since there are no existing options for retrieving a spacecraft before it reenters,” he concludes.

GRAIL

(Continued from page 35)

craft is designed to increase from approximately 62 mi. to 140 mi., says NASA.

A very small orbit trim maneuver executed near the end of mapping cycle 1 will then be used to change the separation drift rate. After this, the mean separation distance will decrease from 140 mi. (225 km) to approximately 40 mi., at the end of mapping cycle 3 (the end of the science phase).

The change in separation distance is needed to meet the GRAIL science objectives. The data collected when the orbiters are closer together will help to determine the local gravity field. When they are farther apart, the data they gather will be more useful for detection and characterization of the lunar core, according to Zuber and other GRAIL geologists.

Instrumentation

The telecom subsystem for GRAIL consists of an S-band transponder, two low-gain antennas, and a single-pole, double-throw coaxial switch used to alternate between two antennas. The low-gain antennas enable the two spacecraft to communicate with each other and are also the mission team’s principal means of contacting them.

The primary science payload on each spacecraft is the lunar gravity ranging system (LGRS), which sends and receives the signals needed for precisely measuring the changes in range between the two orbiters as they fly over lunar terrain of varying density. The LGRS consists of an ultrastable oscillator, a microwave assembly, a time transfer assembly, and the gravity recovery processor assembly.

The ultrastable oscillator provides a steady reference signal that is used by all the instrument subsystems. The microwave assembly converts the oscillator’s reference signal to the Ka-band frequency, which is transmitted to the other orbiter. The time transfer assembly provides a two-way time transfer link between the spacecraft, to both synchronize and measure the clock offset between the two LGRS clocks.

The time transfer assembly generates an S-band signal from the ultrastable oscillator’s reference frequency and sends a GPS-like ranging code to the other spacecraft. The gravity recovery processor assembly combines all the inputs received to produce the radiometric data that will then be downlinked to the ground.