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Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, DC 20554

In the Matters of Mitigation of	)	
	)	
Orbital Debris in the New Space Age	)	IB Docket No. 18-313
	)	
Mitigation of Orbital Debris	)	IB Docket No. 02-54 (Terminated)
	)	

COMMENTS OF THE AEROSPACE CORPORATION

9 December 2018

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THE AEROSPACE CORPORATION

9 December 2018

The Aerospace Corporation welcomes the opportunity to submit comments in response to the Notice of Proposed Rulemaking and Order on Reconsideration, IB Docket No. 18-313, dated October 25, 2018. The Federal Communications Commission (FCC) is seeking comments on the proposed update to the orbital debris mitigation rules for all Commission-authorized satellites, including experimental and amateur satellites. Since all users of space share the orbital debris environment, these rules have the potential to affect the entire community and have implications for future space operations domestically and internationally. The scope of The Aerospace Corporation's comments is limited to those proposed rules in IB Docket No. 18-313 that are within our purview and that time has allowed a thorough consideration of; omissions should not be considered endorsements.

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STATEMENT OF INTEREST

The Aerospace Corporation is uniquely positioned to provide independent and objective analysis of orbital debris mitigation and the long-term sustainability of outer space. Aerospace is a national nonprofit corporation that operates an Federally Funded Research and Development Center (FFRDC) and has approximately 4,000 employees. Its three major locations are in El Segundo, CA, Colorado Springs, CO, and Chantilly, VA. The Aerospace Corporation addresses complex problems with agility, innovation, and objective technical leadership across the space enterprise and other areas of national significance. We assist the U.S. Government in addressing issues vital to national security space and civil space. The Aerospace Corporation supports the most critical programs of the Department of Defense (DoD), the Intelligence Community, the National Aeronautics and Space Administration (NASA) as well as a number of other departments and agencies.

Throughout its history, The Aerospace Corporation has directly supported space operations for our government customers. Specifically, we have a long history supporting space surveillance and space situational awareness and, as such, we have experts on space environment modeling and data collection. For over thirty years, The Aerospace Corporation has studied orbital and reentry debris issues and for over twenty years has operated our Center for Orbital and Reentry Debris Studies (CORDS), which specifically examines operational concerns such as collision avoidance and long-term evolution of the near-Earth debris population. CORDS supports the Air Force and NASA through modeling and engineering analysis and is part of the delegation to the Inter-Agency Space Debris Coordination Committee (IADC). The Aerospace Center for Space Policy and Strategy is dedicated to shaping the future of space by providing nonpartisan research and strategic analysis to decision makers.

Aerospace is providing these comments as an independent organization with relevant expertise. We are not providing these at the direction of, or on behest of any government agency that we support.

SUMMARY

The near-Earth space environment has experienced a significant increase in use over the last two decades due to a burgeoning commercial sector driven by innovation and new investments, as well as by an increase in national security and civil space missions. This increased traffic and potential for space debris poses an increased risk of collision and interference with all future space operations that is harmful to the long-term sustainably of outer space and highlights that space, although big, is a limited resource. This has been recognized for decades and led to the development of Orbital Debris Mitigation Guidelines and Rules implemented by the FCC in 2002. The current call for consideration of rules by the FCC is commendable and represents a step forward toward preventing the creation of additional space debris and supporting long-term sustainability of outer space.

The Aerospace Corporation estimates that nearly all proposed rules in IB Docket No. 18-313 would result in lower levels of future space debris IF implemented and promulgated to include U.S. governmental and international missions, and not only apply only to Commission-authorized commercial, non-governmental missions that access the U.S. market.

While the enforcement of these rules would clearly limit the generation of new debris, they may also impose significant operational constraints and could substantially increase the associated design and operational costs. This could lead to off-shoring by companies to avoid the additional costs. This concern is somewhat mitigated by the need for U.S. market access.

The goal of many of the proposed rules is apparently to ensure compliance with existing standards and to offer specific requirements for several approaches to each debris mitigation goal. An alternative approach could be to require a given level of compliance with each overall debris mitigation goal, such as high disposal success rate, but permit operators sufficient latitude on how to achieve that goal using a combination of approaches. In addition, some of the proposed rules appear unnecessarily complex and could be accomplished using voluntary standards of best practices developed with and by the operators. The key element is post-mission disposal success. Operators should have the freedom to explore multiple ways of achieving the goal, without putting unnecessary constraints on their approach.

Some of the proposed rules are very desirable for supporting long-term sustainability, but may be premature. For example, a location transponder is an excellent idea that should be vigorously pursued, but is still under developed for near-term implementation. A single, world-wide system would be needed to ensure compatibility, together with a central clearing house to collect and share information from the transponders. It is the sense of The Aerospace Corporation, that a more

comprehensive space traffic management framework would need to be developed before a requirement for transponders can be imposed.

The Aerospace Corporation observes that the successful implementation of end-of-life plans is the most critical need for long-term space environment sustainability and debris mitigation. Many studies have shown that the rate of compliance with existing debris mitigation standards, specifically post-mission disposal, is the most impactful method of controlling the on-orbit debris population [1]. The specifics of the end-of-life plan and how to implement a high probability of disposal success should be left to the operator to encourage innovation. Success should be evaluated and achieved at the system level or the constellation level.

Very large constellations pose a significant operational challenge for other space operators, and potentially for the debris environment. It is clear that above some given level, the total impact of any new large constellations should be considered, in addition to rules applied to individual systems. The definition of what constitutes a large constellation needs to be carefully considered prior to setting limits at the system level. For example, while an individual reentry might be below the current 1 in 10,000 threshold for expected casualty, thousands of separate random reentries are likely to accumulate to an unacceptable risk to people on the ground. If it is found that the hazard is substantial, disposal via direct reentry into a safe area might be necessary. In addition, while not considered a serious risk at present, each satellite reentry also creates a number of small debris fragments that, while not a hazard to people on the ground, could be a hazard to aircraft and passengers. Research should be conducted to develop a better understanding of the nature of small surviving debris. Hazards to aircraft might also necessitate regulations to purposefully deorbit satellites from large constellations into a safe area.

While the FCC proposed rule-making on orbital debris mitigation is considered forward leaning and has the opportunity to significantly reduce and mitigate orbital debris, the implementation costs to the operator are of significant concern. There is also a risk of creating different sets of rules, if not sufficiently coordinated, that are exceedingly different from the Orbital Debris Mitigation Standard Practices that apply to all U.S. Government missions and which are largely synchronized with IADC debris mitigation guidelines that were adopted by the *United Nations Committee of Peaceful Uses of Outer Space* in its forty-fifth session in 2008. Although voluntary in nature, many nations have incorporated the UN orbital debris guidelines into their respective national regulatory frameworks.

Recognizing that leadership from the FCC, and the United States writ large, on orbital debris mitigation can lead to international adoption of guidelines, the current effort is only but a first step towards a successful framework that supports commercial innovation and governmental operations, as well as long-term sustainability of outer space.

RESPONSES TO SPECIFIC ITEMS IN THE PUBLIC NOTICE

A. Control of Debris Released Normal Operations

Paragraphs 18-21

- These paragraphs are consistent with the current U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) as applicable to U.S. Government missions. We endorse the addition, as proposed, to minimize the generation of debris from deployment mechanisms and other similar operations.

B. Minimizing Debris from Persistent Liquids

Paragraphs 22-23.

- An important consideration with any rules relating to liquids is the ability to distinguish between releases that could result in droplets or solids that could be a collision threat and those that dissipate or are too small to cause damage on impact. There are a number of beneficial operations including venting or using excess propellant and oxidizer that constitute release of liquids that are less likely to cause impact damage.
- We recommend that this rule be clarified to explicitly permit the venting of volatile liquids and pressurants that could pose future fragmentation risks but will not form hazardous droplets.

C. Safe Flight Rules

C.1 Quantifying Collision Risk

- This section discusses a requirement for a collision risk assessment for new systems. In general, we agree that the intent of this section is consistent with the ODMSP and with best practices. Most operators of large constellations plan to perform active collision avoidance, and to have a requirement that all operators explicitly address this in their plan is beneficial.

Quantifying Collision Risk, Paragraph 26.

- We recommend that a "large constellation" be explicitly defined based on a combination of numbers of satellites, and the total mass and area of the satellites. An aggregate risk should be applied to large constellations, while individual risk should be applied to small systems. The definition should be based on the potential impact on the space environment from catastrophic breakups in space and on the hazards to people on the ground (and potentially aircraft) from debris surviving satellite reentries. For in-orbit incidents this should be a function of the number of sizable debris objects produced (mass) and the cumulative probability of impact (object years or area

years). In the case of reentry incidents, hazardous impact should be based on the disposal strategy, and the number and mass of satellites reentering per year.

- We recommend that the debris mitigation requirement be applied to all satellites, not only NGSO (Non-Geo Stationary Orbit) satellites, i.e., GSO (Geostationary Orbit) satellites should not be excluded because they can also be involved in collisions that would generate large amounts of untrackable, long-term debris in the GEO region. This requirement has already been implemented in Air Force Instruction (AFI) 91-217.
- We recommend limiting the period of assessing collision probability to a finite time such as 100 years. This will make assessment feasible for satellites that have an orbital lifetime greater than 100 years. This has also been implemented in AFI 91-217 (although the maximum time period for assessment is 200 years at the present time).
- We recommend that in risk assessment it be permitted to account for the reduction in collision probability due to active collision avoidance (COLA) during the operational mission. This is permitted in AFI 91-217. It would encourage good COLA practices and could enable even large numbers of satellites to meet collision risk thresholds. We recommend that a COLA target threshold on collision probability (e.g., $1x10^{-6}$ in AFI 91-217) be used rather than zero.
- Including the application of collision avoidance maneuvers in risk reduction is a reasonable approach as it encourages active measures that reduce the likelihood of large debris generation events. Typically, collision avoidance maneuvers decrease the probability of collision but do not eliminate it. The amount of decrease is often related to the size of the collision avoidance maneuver and thus fuel expended. An overall lifetime collision probability can be used by satellite operators to scale the level of their collision avoidance maneuvers and balance collision prevention/debris generation with fuel expenditure.
- We recommend defining large objects as those of size >10 cm. Otherwise the 0.001 collision threshold may not be achievable. This has already been implemented in NASA Standard 8719.14 and in AFI 91-217. These changes would also be consistent with the recent proposed changes to the ODMSP.
- Typically, models assume a tracking limit of approximately 10 cm for LEO (Low Earth Orbit) regardless of object size, altitude, or reflectivity. Such simplified assumptions can lead to unsound regulatory decisions. In addition, objects that are 10 cm or larger will produce larger amounts of debris during a catastrophic breakup. The NASA debris mitigation standard is attempting to prevent such catastrophic breakups of large objects. As the tracking size limit decreases the potential collisions with smaller objects will transition to non-catastrophic events that produce much less debris. The effective atmospheric drag, a function of area/mass ratio, increases with decreasing mass of the satellite leading to faster deorbit time for smaller satellites. Setting a size threshold

should consider relative velocities (GEO vs LEO) and should be based on mass and not a perceived tracking limit.

Quantifying Collision Risk, Paragraph 27.

- The success rate for post-mission disposal is one of the more important parameters of debris mitigation, though determining probability can be difficult. This requirement for small object collision probabilities that prevent post-mission disposal should be consistent with any additional requirements related to post-mission disposal success rates for the satellites, including the application and implications for constellations and their aggregate calculations. If considering such a rule in aggregate, one approach would be to make the aggregate probability threshold greater than for a single satellite, but less than the product of that probability by the number of satellites in the constellation. This will help balance the cost for compliance with the benefits to the debris environment. This potential rule is tied to orbit choice for systems and could be used to numerically enforce the concept in paragraph 34 requiring propulsion capabilities.

Quantifying Collision Risk, Paragraph 28.

- As space becomes more crowded, new operators should have to explicitly consider the impact on their neighbors. However, it should be noted that new operators may not have access to complete information on all objects in their proposed vicinity. Some of these may be foreign systems, and some may be national security systems. A central space traffic management organization may be better suited to work towards preventing collisions. It may not be feasible for an operator to fully comply with these rules absent such an organization.

C.2 Orbit Selection

- This section contains several concepts that continue the theme of requiring explicit consideration of the space environment and neighboring operators when applying for a license, and we agree that this is both necessary and will contribute to a safer environment and lower impact on neighboring systems. We believe that the best rules focus on the goal, while permitting maximum flexibility in the approach to achieving that goal.

Orbit Selection, Paragraph 30.

- The International Space Station (ISS) is the first exemplar of a permanently manned object, but other manned systems will likely be launched in the future, probably at similar altitudes to the ISS. The rule should be clarified to ensure new systems are capable of avoiding permanent or long-term manned objects.

- The key requirement for this rule should be active collision avoidance. A new system should demonstrate that it can avoid a collision as it transits a manned object's altitude without requiring that system to maneuver. If this can be accomplished via drag modification or some similar approach, propulsion may not be necessary. The rule might be stated in terms of reducing the probability of collision to less than some threshold within a specified warning period. An important consideration in the implementation of this rule is the ability to implement post-mission disposal. If active control is required when passing through crewed altitudes, it may preclude the ability of many systems to perform proper disposal as many systems use atmospheric drag to dispose after the completion of their mission.

Orbit Selection, Paragraph 31

- The requirement to justify orbits that will not naturally comply with the 25-year rule is clearly intended to prevent long-term debris from failure to execute post-mission disposal. However, we recommend specifying a minimum probability of success for post-mission disposal as the overarching goal as opposed to specific mandates that limit operator options for meeting the overall disposal rate goal.

Orbit Selection, Paragraph 32

- Including a statement on the rationale for orbit choice, particularly for short-lived systems, will cause operators to consider if a longer disposal lifetime is really necessary. The consensus of the international debris community is that the success rate for the disposal is the most important factor for debris mitigation, even if the disposal period is less than the current 25-year standard.

Orbit Selection, Paragraph 33

- This proposal is related to paragraphs 26 and 27 in that the probabilities of collision will be higher in more highly populated regions of space which would impact the ability of constellations, especially larger ones, to meet the aggregate requirements in paragraphs 26 and 27. In theory one should be able to capture the purpose in this proposed rule by carefully choosing the restrictions in paragraphs 26 and 27.

Orbit Selection, Paragraph 34

- It is possible to include the essence of this requirement with paragraph 26 on collisions with large objects. One of the methods of reducing this collision probability in congested orbits is to use a collision avoidance plan during both operations and disposal. This would place the burden for collision avoidance on systems with large numbers of satellites, due to the aggregated nature of the rule, and for systems in more populated orbits.

Orbit Selection, Paragraph 35

- It has been found through studies that orbit separation, especially between constellation planes, can significantly reduce conjunctions and potential collisions [2]. Some control over the quality of orbit maintenance would help maintain separations. Using the current public covariance information, it is necessary to keep a 10 km separation from another object to have a collision probability on the order of $1x10^{-6}$. With natural orbit variations, a minimum altitude spacing of approximately 20 km would be necessary. However, this is only effective if the orbit is circular. Orbital separation is a good goal, but the rule may not be practical.

C.3 Tracking and Data Sharing

- This section discusses requirements that would make new systems easier to track, and make presumably better owner-operator position data available for collision assessment by others. This is a beneficial and necessary goal, and steps in this direction should be encouraged.

Tracking and Data Sharing, paragraph 36

- Requiring trackability is more important than defining size of objects. The 10 cm tracking size limit should be considered only a rule of thumb for LEO objects as it includes many simplifying assumptions. Using current radar systems, it is unlikely that 10x10x10 cm objects could be reliably tracked at altitudes higher than LEO without additional signature enhancements. The often-assumed size for reliable tracking at geostationary altitudes by the current Space Surveillance Network (SSN) is 1 m, which is done primarily with optical sensors. Given this value, there would be a gap between 10 cm and 1 m where an object could be untrackable and not required to have additional signature enhancements. The tracking levels will likely undergo a significant change with the activation of the Space Fence which will make objects smaller than 10 cm (estimates range from 2 to 5 cm), trackable at least at LEO altitudes. Both of these considerations make setting an effective threshold more difficult. Given the number of variables and the changing tracking capabilities, a more appropriate rule would be to require trackability rather than defining trackability simply by size. We recommend that the rule be to require trackability, but to include both the 10x10x10 cm minimum size for LEO and the 1x1 m minimum size for GEO as exemplars. We concur that smaller systems must be demonstrated case by case.
- Hardware such as transponders or other signature enhancements and data sharing would benefit trackability, but it is not clear that any commercial transponder hardware or comprehensive data sharing methods currently exist. Nonetheless, without requirements there is less motivation to develop the necessary hardware and/or data sharing capabilities. A potential rule could consider a

requirement of signature enhancements, such as radar reflectors, for small objects in orbits well above LEO since such technologies are available.

Tracking and Data Sharing, Paragraph 37

- Requiring data sharing with the 18th Space Control Squadron (SPCS) or a future civilian agency has potential to improve the currency and accuracy of conjunction assessments. One consideration is whether the 18th SPCS or a future civilian agency would be in a position to use this information if it were provided. The recipient of the data will need to define the format and mechanism of the data sharing as well as accuracy verification. Also, worth considering is that with the increase of automation in orbit maintenance, the number and frequency of maneuvers that satellites perform could significantly increase. Requiring appropriate data sharing is important and would set the stage for future improvements for the 18th SPCS or a potential civilian agency to use the improved data.

Tracking and Data Sharing, Paragraph 38

- Operators should provide a plan for how collision avoidance would be accomplished. This plan would tie into paragraph 26 and the need for limiting the collision probability with large objects. The collision avoidance plan should include coordination between operators even if one satellite is unable to maneuver.

C.4 Maneuverability, paragraph 39

- We agree that information on maneuverability should also be included as part of a collision avoidance plan for each system.

C.5 Multi-Satellite Deployments, paragraphs 40-41

- A re-contact analysis should be conducted for multi-payload missions to verify that the deployment sequence will not result in collisions between the deployed objects. The length of time for this analysis will vary depending on deployment characteristics and orbit but should be for at least tens of orbits in LEO after deployment to adequately identify possible collisions. This approach also applies to the question in paragraph 41 on obtaining information about the overall launch from the launch provider.

C.6 Design Reliability, paragraphs 42-43

- We agree that large constellations should face additional scrutiny and have additional considerations for space debris prevention and mitigation. A revision of the ODMSP is also considering separate rules at the constellation level for large constellations. The total impact of a

large constellation on the space operations environment, and cumulative reentry should be considered, and additional rules and scrutiny should be applied.

- The probability of success of post-mission disposal in terms of design reliability should be a key consideration, as discussed in paragraph 27 above and 59 below. We recommend specifying this as a goal, rather than attempting to define a specific reliability per spacecraft. Maximum flexibility should be permitted in how this success rate is achieved. For example, rather than seeking extremely high-reliability in the design of individual spacecraft, a constellation-level design might include active retrieval as part of the mission concept or operational procedures to increase post-mission disposal reliability and ensure successful removal.
- The definition of what constitutes a "large" constellation should consider more than the number of satellites. The risk to the environment is also dependent on the mass of the object and cross section of the object.[2] A CubeSat is less likely to be hit and will not result in thousands of trackable, threatening debris objects, but a 1000 kg satellite breakup might. The mass, and the potential threat to the environment from failed objects should be a consideration in the reliability requirement. A metric could be defined using a combination of the number of separate objects, the time in orbit, the collision area and the mass in orbit.

D. Post-Mission Disposal

- As stated above, we believe that the probability of success for the disposal of an object at the end of its orbital life is the most critical aspect that should be considered in a rulemaking to prevent space debris. Implementing such a rule would, particularly for large constellations, accomplish the intent of many of the additional rules being proposed.

Paragraphs 44-45

- The document should encourage disposal techniques that minimize time in orbit with a preference for highly reliable direct disposal into a safe area in order to minimize the risk to people on the ground and in aircraft. The U.S. should support an effort to develop and set a maximum acceptable yearly cumulative casualty expectation for a constellation and require that all satellites in a constellation have highly reliable means of direct disposal if that limit is exceeded.

D.1 Probability of Success of Disposal Method, paragraph 46

- Disposal reliability has been identified by a number of studies as one of the most critical factors in the mitigation of debris, especially in the presence of large numbers of satellites [1]. These studies and analyses on post-mission disposal success rates based on historical launches identified a value of 0.9 as sufficient. Several instructions and standards, including AFI 91-217, adopted this threshold and the next version of ISO debris mitigation standard 24113 is currently considering the

same threshold. It should be noted that this value should represent a probability of successful post-mission disposal versus a "spacecraft reliability" as there are a number of options, including operations practices, beyond conventional system reliability that can be used to achieve the required success rate. For launch traffic significantly higher than historical levels, especially considering large LEO constellations, the rate of probability may need to be higher.

Probability of Success of Disposal Method, paragraph 48

- As stated in the discussion of paragraph 46 above, post-mission disposal success rates for large constellations, which will involve significantly higher launch traffic than historical trends, will need to be higher than 0.9 to limit growth in the debris environment. The use of low altitude checkout orbits as proposed here is one way to achieve the higher success rates. Failures in the checkout orbit would naturally dispose. A result of removing the early failures would increase the post-mission disposal success probability of the remaining systems.
- However, it should be noted that requiring low-altitude checkout means that potentially large numbers of satellites will be moving up through orbits of other satellites as they relocate to their operational orbits. Without accurate and timely conjunction warnings, this additional traffic could have the unintended consequence of increasing the debris population. A requirement for an active collision avoidance plan would mitigate these effects.
- More importantly, this rule would potentially have considerable impact on satellite costs. While it could ensure that a system which failed early in life would still reenter within 25 years, and would not likely interfere with most operational systems, it would also eliminate direct orbit injection, and require that each system have considerable maneuver capability. This puts a significant and costly design constraint on a system, and may preclude more innovative approaches for mitigating debris. As noted above, the key element is post-mission disposal success. Operators should have the freedom to explore multiple ways of achieving the goal, without putting unnecessary constraints on their approach.

Probability of Success of Disposal Method, paragraph 49, 50

- We agree that requiring the automatic initiation of disposal as a fail-safe for lack of contact would reduce the amount of material left in orbit. However, as we note elsewhere in the discussions of the risk of reentry, the accumulated risk of multiple reentries from a constellation might require <u>targeted</u> reentry into a safe area. This cumulative risk at the constellation level should be considered when contemplating automated disposal.
- In addition, we note that designing systems that initiate automatic disposal of satellites is difficult as the system must identify failures that are non-recoverable and act only on those. The system would

also require very high reliability to ensure that it does not misidentify failures. Currently there are few independent disposal systems that have demonstrated high reliability and effectiveness. This may change over the next several years as a number of systems, particularly drag enhancement devices, are included on satellites and activated at end of life.

Probability of Success of Disposal Method, paragraph 51

- A high disposal success rate should be considered most critical for large constellations of satellites due to the number and total mass that could potentially create debris in orbit. As described earlier, a specific definition of "large" for a constellation (discussion of paragraph 26) should be considered as several factors contribute to the overall impact on the debris environment. Such factors include the number of satellites in the constellation, the total mass placed into orbit, the number of years on orbit, the total collision area of the satellites, and the cumulative yearly reentry hazard, all of which are affected by replenishment frequency.

Probability of Success of Disposal Method, paragraph 52

- Most studies on the mitigation and remediation of space debris conclude that leaving mass in orbit contributes to the growth of debris [1,2,10]. A reasonable goal would be to minimize the mass left in orbit including the removal of all objects from orbit as soon as possible at the end of the mission.
- Studies have determined that using a permanent disposal orbit above LEO can result in future collisions of the disposed satellites generating debris that will spill into the LEO region [6]. For this reason, it is not recommended that LEO satellites be disposed of above 2000 km.
- A soon-to-be-published study [5] shows that reentries of a large number of satellites could cause a significant increase in risk to people on the ground and in aircraft due to constellation debris surviving reentries. The study concludes that the operator of a large constellation (constellation with more than ~50 satellites of any size) should provide information on design lifetime, the strategy for removal and replacement, the maximum number of satellites expected to reenter in a year, and the cumulative casualty expectation for that case over the lifetime of the constellation. In the meantime, technical efforts are necessary to measure the number, size, and properties of small debris that survive reentries as that data is critical to understanding the hazards to aircraft.

Probability of Success of Disposal Method, paragraph 53

- Direct retrieval is one option of reaching the high post-mission disposal success rates needed for large constellations. Although there are several systems in development for direct retrieval, it is important to realize that they have not been tested thoroughly. We recommend that direct retrieval be demonstrated before implementing a requirement for large constellations. Direct retrieval should

not be considered the primary disposal approach given the uncertainties in the near-term availability of retrieval systems and their cost.

Probability of Success of Disposal Method, paragraph 54

- When a vehicle includes a grappling fixture or other attachment or tracking devices, the process of direct retrieval is made significantly easier than retrieving a non-cooperative object that does not include such devices. This should be taken into consideration when evaluating the use of direct retrieval as a means of disposal. Grappling fixtures, radar corner reflectors, and optical reflectors are simple, relatively low-cost devices. It is prudent to include these in spacecraft designs even if there are no active plans for retrieval.

Probability of Success of Disposal Method, paragraph 55-57

- For disposal above LEO, low eccentricity growth and high eccentricity-growth orbits have been extensively studied for disposal and are well understood [3,4,7-9]. For typical spacecraft, eccentricity growth is determined by Sun and Moon gravity perturbations. The advantage of low eccentricity growth is that potential interference with operational satellites will be delayed. The advantage of high eccentricity growth is that the probability of collisions between disposed objects, and hence potential generation of untrackable debris near the mission orbit, will be reduced compared to a nearby low-eccentricity growth orbit with disposed satellites accumulating in a smaller volume.
- Note that in general for orbits with inclination above 50 degrees, disposal orbits are not truly stable. Such orbits have either low or high eccentricity growth during the first few decades [3]. Orbits with lower inclination will, in general, have a fixed amplitude oscillation in eccentricity. If the spacecraft has a very high-area-to-mass ratio, eccentricity will grow due to solar radiation pressure. The relative effectiveness and achievability of the two options will vary with orbit type. For example, high eccentricity growth will, in general, not be an option for orbits with inclination below 50 degrees. Spacecraft design may preclude changing the argument of perigee, and therefore only partial stabilization for orbits with inclination above 50 degrees can be achieved by eccentricity minimization alone. A third option would be to target disposal orbit eccentricity and argument of perigee so that eccentricity initially decreases but then increases such that COLA interference with operational satellites would be temporarily delayed in a more controlled manner than can be achieved by trying to change the argument of perigee for a near circular orbit.
- For the high eccentricity growth option, since these orbits may cross LEO or GEO, a recommended guideline would be to limit cumulative times spent by a spacecraft in LEO and GEO, respectively, with a maximum time period for the assessment (e.g., 200 years for objects disposed near the GNSS (Global Navigation Satellite System) systems since it can take that long for them to reach

LEO and GEO) [4]. A limit of 25 years spent by a spacecraft in LEO would yield the equivalent effect (in terms of limiting collision risk) of the 25-year total lifetime limit for LEO-resident objects. It would also avoid disposal orbits close to LEO or GEO that have a low level of eccentricity growth which could result in significant dwell times in LEO or GEO. An analysis should be performed to see if the assessment results are sensitive to expected variation in the disposal orbit elements due to maneuver and passivation (blowdown) dispersions. For select disposal orbit regions (typically higher initial eccentricity), the orbit evolution may exhibit some chaotic behavior due to resonances associated with apparent solar motion or with nodal regression of the Moon's orbit about the Earth.

D.2 Post-Mission Lifetime, Paragraphs 58-59

- A requirement should encourage disposal techniques that minimize time in orbit with a preference for direct disposal into a safe area to minimize the risk to people on the ground and in aircraft. This could be a mandated option in the long term. (The U.S. should support an effort to develop and set a maximum acceptable yearly cumulative casualty expectation and require that all satellites in a constellation have highly reliable means of direct disposal if that limit is exceeded. The U.S. should encourage development of automated, failsafe techniques for controlled disposal into a safe area.)
- Consideration of collision avoidance and collision risk should be the responsibility of an operator for the entire period that a system is in orbit, including post-mission. In general, a system should be encouraged to limit its orbital lifetime.

D.3 Casualty Risk Assessment, Paragraphs 60-62

- These items seek consistency with the ODMSP and IADC guidelines which would be beneficial.
- As previously discussed on paragraph 52 and elsewhere, a cumulative metric should be applied to “large” constellations. Metrics for reentry risk, collision risk, and post-mission disposal success should be consistently treated in the aggregate for large constellations.
- We recommend changing "probability of human casualty" to "risk of human casualty" throughout the proposed regulation. Risk of human casualty, also known as casualty expectation, has units of "people" and has an upper threshold of total people exposed to becoming a casualty. This is the term used in orbital debris mitigation. This value is not a probability, which would have an upper threshold of 1 (or 100%).

E. Proximity Operations

Paragraph 68

- Disclosing the intent and the ability to perform proximity operations should be considered part of the overall assessment of flight safety. If a system is being assessed to have a life probability of collision per paragraph 26, proximity operations would certainly be part of such an assessment.
- An overarching theme to many of these proposed rules is greater communication between space operators for flight safety and collision avoidance. This should automatically include the 18th SPCS or a new civil space traffic management organization.

F. Operational Rules

Orbit Raising, paragraph 70-71

- We agree that orbit raising maneuvers for NGSO spacecraft should also be coordinated. This is particularly important for slow spiral maneuvers using low-thrust propulsion systems.
- This rule should be modified to include ALL orbit change maneuvers, including orbit lowering for disposal.
- It should be noted that it would be difficult for LEO operators to perform this coordination bilaterally with all other operators. This is a case where a central space traffic management organization would be essential in providing coordination, and requiring all operators to file "flight plans".

Maintaining Ephemeris Data, paragraph 72-73

- We agree that maintaining ephemeris data would result in a significant improvement of flight safety. All operators should make their ephemeris data readily available, in *real-time*. This is another case where a central space traffic management organization would be of marked assistance in collecting the information.

Telemetry, Tracking, and Command Encryption, paragraph 74-75

- Encrypting command and telemetry is prudent. However, we estimate that it would be extraordinarily difficult to commandeer a satellite and use it to intentionally harm another spacecraft if it were not designed to do so. The greatest risk to other systems would be that the primary operator could no longer successfully execute post-mission disposal, effectively rendering the system as debris.
- A separate rule for encryption seems unnecessary. The intent of this rule could be accomplished by evaluating encryption as a factor in success of collision avoidance and post-mission disposal.

H. Scope of Rules

Non-U.S. Licensed Satellites, paragraph 85-87

- This proposed rule set could potentially impose much stricter debris mitigation guidelines on U.S. commercial systems than might be the case for non-U.S. systems. Imposing similar restrictions on systems seeking access to the U.S. market would be important to preclude "off-shoring" for operators seeking to avoid restrictions. The U.S. should work to harmonize these rules with those of other spacefaring nations.

Appendix A – Proposed Rules

Part 5 – Experimental Radio Service

The bulk of our comments have been recorded in the discussions above. The following are repeated with respect to the specific rules:

(2)(b)(2) Aggregated collision probability will significantly increase the burden on large constellation operators by factors of 100s to 1000s depending on the proposed constellation size. Although this is good for controlling the debris environment it may be excessively expensive for operators. If meeting this requirement is excessively burdensome it may be possible to meet the same objectives for post-mission disposal success by combining this factor into the overall requirement for post-mission disposal success. Another option would be to consider an aggregate value greater than for a single satellite but significantly less than for the total constellation.

(4)(i)(A) Aggregated collision probability with large objects will significantly increase the burden on large constellation operators by factors of 100s to 1000s depending on the proposed constellation size. This can be mitigated by using operational orbits with low existing populations and applying aggressive collision avoidance standards. It is not clear whether the collision avoidance requirements will become excessive. There is no designation of what "large object" applies to. This could range from other intact objects to all trackable debris. In the near future, that could mean differences in order of magnitude in the conjunction rates.

(5)(ii) The applicant should be required to provide a statement of conditions during the in-orbit operation of their space stations that would lead to initiation of a disposal action (e.g. communication failure, failure of critical payload component/system). The applicant should provide details of that disposal action and verify by analysis that the action will meet the

90% disposal requirement for all mission-ending failures believed possible. This is a component of the general need for high post-mission disposal success rates also discussed in reference to paragraphs 46, 48, 51 and 53.

(5)(iii) A soon-to-be-published study [5] shows that reentries of a large number of satellites could cause significantly increased risks to people and aircraft due to debris surviving reentries of satellite being disposed from the constellations. This work supports the notion that a proposer of a large constellation should provide information on the design lifetime of constellation satellites, the strategy for removal and replacement of satellites in the constellation, the maximum number of satellites expected to reenter in a year, and the cumulative casualty expectation for that case during the lifetime of the constellation. (In the meantime, the U.S. should also make efforts to measure the number, size, and properties of small debris surviving spacecraft reentries. That information is critical to understanding the hazard such reentries pose to aircraft.)

(5)(iii) The document should encourage disposal techniques that minimize time in orbit with a preference for automated direct disposal into a safe area--direct disposal into a safe area would minimize the risk to people on the ground and in aircraft. (The U.S. should support an effort develop and set a maximum acceptable yearly cumulative casualty expectation and require that all satellites in a constellation have automated means of direct disposal if that limit is exceeded.)

(5)(iii)(A) The post-mission disposal success rate has been found in numerous studies to be one of the most critical factors in mitigating the growth of the debris environment. Although it has been found that a post-mission disposal success rate of 0.9 can be effective in limiting the growth of the debris environment, if there is significant increase in launch traffic above the current levels it may be necessary to have a higher post-mission disposal success rate to achieve similar levels of debris growth limits.

(5)(iii)(C) Is the goal to have a probability of human casualty or an expected casualty estimate? They are not always similar as expected casualty can be greater than 1. A value for acceptable expected casualties or probability of human casualty is not provided. There is a value provided in ODMSP (1:10000) which perhaps should also be reflected here.

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