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COMPARISONS OF SPACE DEBRIS ESTIMATES

Gregory H. Canavan, O'Dean P. Judd, and Robert F. Naka

Debris is thought to be a hazard to space systems through impact and cascading. The current environment is assessed as not threatening to defense systems. Projected reductions in launch rates to LEO should delay concerns for centuries. There is agreement between AFSPC and NASA analyses on catalogs and collision rates, but not on fragmentation rates. Experiments in the laboratory, field, and space are consistent with AFSPC estimates of the number of fragments per collision. A more careful treatment of growth rates greatly reduces long-term stability issues. Space debris has not been shown to be an issue in coming centuries; thus, it does not appear necessary for the Air Force to take additional steps to mitigate it.

Issue: Spacecraft, boosters, and fragments in orbit represent hazards to space vehicles. It is also argued that in the next century, collisions between debris particles could trigger a cascade of small particles that would preclude activity in low Earth orbit (LEO). Those concerns have generated pressure for constraints on military space operations and for significant modifications of military launchers and spacecraft. Thus, during 1995-6 the Air Force Scientific Advisory Board (AF SAB) performed a study of technical aspects of the debris problem, which was independent of the assessments of the Air Force's Space Command (AFSPC) and of NASA, the principal advocate of the cascade hypothesis and for placing constraints on space operations to reduce debris growth. However, most of the work on space debris has been performed by AFSPC and NASA, so in part this discussion takes the form of an assessment of their efforts, in which both were very cooperative. The Study developed a thorough understanding of their models and data bases, identified their main areas of disagreement, and quantified the impact of these disagreements. It reviewed the current status and uncertainties in radar and optical observations; launch, deployment, explosion, and decay rates; and the number and distribution of fragments produced by explosions and collisions. It resolved the most pressing issues, and bounded the rest.

These studies made it possible to address the overall uncertainties in the impact hazard at low altitudes and the likelihood of cascading at higher altitudes, both of which now appear somewhat remote. They also provided a foundation for comments on the mitigation measures proposed for the Shuttle, Space Station, and unmanned spacecraft in the *NASA Safety Report*,¹ the National Academy of Science—National Research Council *Orbital Debris*,² the Office of Science and Technology Policy (OSTP) *Interagency Report on Orbital Debris*,³ which is the basis for the current Interagency Study, and the United Nations Committee on Peaceful Uses of Outer Space (COPUOUS) deliberations, which are based on the earlier NASA analyses.

Catalogs are data bases containing the orbital elements of objects that have been detected

and tracked reliably. Of principal interest in this study are the catalogs of the roughly 5,300 objects in low Earth orbit (LEO) with diameters larger than a few tens of centimeters, which can be tracked accurately by the AFSPC ground-based UHF radars. Those objects are the most closely related to the concerns discussed above. The Study tested the consistency of predictions of the amount of debris at various altitudes in LEO by using AFSPC's published orbital elements together with NASA's orbital averaging techniques,⁴ which it tested independently to predict AFSPC fluxes that can be compared directly with NASA's. The fluxes are shown as functions of altitude in Fig. 1.⁵ The predictions are within a few tens of percent at all altitudes other than 400 km. This agreement primarily indicates consistency between AFSPC and NASA data bases and averaging, as NASA does not take independent catalog data. However it does indicate that there are no serious discrepancies between their catalogs, which was not clear at the beginning of the Study.

Figure 2 shows the density of particles as a function of size and altitude in LEO. The sharp spike at 950 km of 3-10 m² satellites and at 1,450 km of 0.3-1 m² satellites are quite prominent, as are the broader distributions of smaller debris objects there. Other peaks for large satellites at lower altitudes are also visible, though less pronounced. While they contribute little to satellite number, they contribute significantly to the total area and rates there. Similar features are seen in NASA figures.⁶ However, both predictions are ultimately based on AFSPC's UHF observations and catalog, so this agreement is again primarily a test of data consistency and averaging procedures.

Figure 3 shows the variation of the cumulative flux of particles larger than a given diameter at several altitudes as measured by AFSPC UHF, Arecibo 430 MHz, and Haystack x-band radars. In accord with Fig. 2, for the ≥ 20 cm diameters for which they are defined, the AFSPC flux is higher by about an order of magnitude at 600-1,000 km than at 600 km. *Orbital Debris* extends these curves below 10 cm,⁷ but it is clear from Fig. 2 that UHF measurements are incomplete below a radar cross section (RCS) of ≈ 0.03 m², or diameter of ≈ 20 cm.

For diameters > 20 cm, the Haystack fluxes for 400 and 900 km lie between the AFSPC fluxes, but the Haystack error bars are an order of magnitude larger than the mean, so the agreement is not meaningful. Haystack's narrow beam sees too few catalog particles to produce meaningful statistics. That is also the reason for Haystack's large error bars for smaller particles. Arecibo's large error bars for measurements for > 2 cm particles result from its short run time of only a few days. *Orbital Debris* indicates small error bars for smaller objects, but they are questionable for reasons discussed below. Overall, there does not appear to be a usable correlation between observations by different radars for particles of any size, or an unambiguous measurement of the flux of particles of any diameter smaller than about 20 cm.

For diameter $D < 1$ cm, the debris distributions in Fig. 3 scale approximately as $1/D^4$, which is also the scaling attributed to the meteoroid flux in that diameter range. In the range $1 \text{ cm} < D < 10 \text{ cm}$, the flux scales roughly as $1/D^{3/2}$. For $10 \text{ cm} < D < 6 \text{ m}$, the flux scales roughly as

1/N/D. This scaling means that most of the particles are contained in the lower ranges, while most the mass is in the upper range above 10 cm, which roughly coincides with the catalog particles measured by UHF. Given the uncertainties indicated above, the partition is not rigorous, but at present most of the mass appears to be measured by the UHF radars, which see little of the flux, while most of the flux is measured by shorter frequency radars, which see little of the mass.

There is a gap in the data for diameters between about 0.01 and 0.1 cm, which masks whether the two sets of data originate from the same phenomenon. The most extensive data for smaller diameters is from the Long Duration Exposure Facility (LDEF). It was in orbit for 6 years with instrumented skin sensors that produced data for the impact of particles a few tenths of a millimeter across. There are also roughly characterized examples of small impacts on the Space Shuttle, Mir, and other structures, e.g., on April 1994 a Shuttle window was cracked by a ≈ 0.04 cm paint chip.⁸ However, modest amounts of material can shield against particles of that size, so the discussion below largely concentrates on the mm to cm particles that are more of a challenge for shielding and the tens of cm to meter particles that are of interest for collisional cascading.

An unresolved catalog issue is the operational sensitivity of UHF radars to small objects, which impacts estimates of the completeness of the catalog at 10-20 cm and hence estimates of the expected frequency of Shuttle debris avoidance maneuvers. Figure 4 shows the AFSPC SSN and NASA "Evolve" catalogs as functions of altitude.⁹ The top curve is NASA's catalog of > 10 cm objects. It is a factor of 2 to 4 above the lower curve, which is the AFSPC SSN catalog. NASA attributes this discrepancy, and the fact that the Evolve curve for objects > 20 cm roughly agrees with the SSN catalog, to a UHF radar sensitivity of only 20 cm, because . This explanation is plausible but not unique. NASA's Evolve model has no direct measurement of the flux of particles < 20 cm, which are underrepresented in the AFSPC catalog, so it must estimate them by means other than direct observations. Thus, the comparison measures in part the accuracy of that extrapolation. NASA's Evolve could underestimate orbital decay of small fragments and hence overestimate the flux of 10 to 20 cm objects. At present, there appears to be a factor of 2 to 4 discrepancy on catalog completeness and on the explanation for it, which induces a factor of 2 to 4 uncertainty in the expected frequency of Shuttle avoidance maneuvers.

A factor of 2 to 4 improvement in sensitivity would be useful but not pivotal in AFSPC's missile warning because most valid targets present cross sections larger than 10 cm, not smaller. Thus, refining the 10-20 cm catalog is primarily of interest for catalog completeness and Shuttle avoidance maneuvers. Those are not areas of primary AFSPC responsibility—although NASA has suggested that AFSPC assume responsibility for them. AFSPC radars could be improved with better calibration, reporting, and astrodynamics, which need not be overly expensive. Those improvements would have a positive impact on both space surveillance and the AFSPC's ability to provide the best space environments possible with current sensors and facilities. Further steps

would be expensive.

The second unresolved catalog issue is NASA's extrapolation of UHF measurements to ≈ 1 cm diameter particles to provide detailed environments for manned space missions. AFSPC has resisted the extrapolation of its UHF measurements to particles that small because they are unobservable with UHF sensors. NASA has also argued for new shorter wavelength radars that could make those measurements directly. The Study reviewed the proposed technology for the dedicated x-band radars required to detect and track ≈ 1 cm particles. While feasible,¹⁰ the system could cost in excess of \$1B and would not contribute significantly to the DoD's missile warning and surveillance missions. If NASA needs such a capability, it would appear appropriate for NASA to develop those sensors and capabilities separately. Elements in NASA have argued in interagency forums that AFSPC should develop this ≈ 1 cm catalog as part of its current DoD mission, but that does not appear logical. As this issue does not appear to require prompt action on the basis of the data and analysis presented below, the Study took no position on it.

Debris size and shape. Radars do not measure debris particle sizes and shapes. They measure an electrical return signal, which implies a radar cross section (RCS), from which a geometric cross section is inferred, from which the object's linear dimensions are estimated through some model. Each step is progressively more indirect, particularly the last two, due to the irregularity of radar and geometric cross sections.¹¹ In Fig. 3, at diameters of 10 to 20 cm, the uncertainties are quite large. Even at diameters of a few centimeters, the uncertainties are an order of magnitude larger than the mean values. For that reason, debris distributions must be interpreted as the means of functions of large variance. An exception is the AFSPC UHF measurements at > 20 cm. They represent many decades of data, which has produced much smaller variances.

These uncertainties in size and shape are important in designing spacecraft shielding. Fragments range from spheres to flat plates, with all possible complicated shapes in between, whose interactions with shields differ greatly. For example, a flat plate that hits a Whipple shield squarely can punch a hole through it and an underlying surface that should stop a 10-fold more massive spherical particle.¹² Thus, to characterize debris to the level required for full understanding of the spacecraft shielding problem, would required measurements of sizes and shapes down into the 1 cm regime, which is an order of magnitude more difficult than the measurements attempted today. There are relevant technologies—x-band radar arrays, millimeter radars, lidars—but they represent difficult and expensive steps beyond today's UHF radars.

Optical sensors. The Air Force has optical sensors that can potentially contribute to the resolution of these debris issues. Indeed, AFSPC's 1 m aperture GEODSS telescopes were built for specifically this application. Their current performance is limited by obsolete focal planes, electronics, and computers, but their focal planes are being replaced by sensitive, large-format, charge-coupled device (CCD) cameras with high speed readout electronics and their computers are

being upgraded to modern work stations, so they should soon be capable of searching large volumes of space to about 22nd magnitude (≈ 1 cm object at GEO), which should give significant improvements in resolution, spectral, and search capability. The GEODSS telescopes are currently a scarce asset, so they are primarily tasked to look for military objects at GEO, which leaves little time to search for debris at LEO. However, a few upgraded GEODSS telescopes should provide enough capacity to satisfy requirements at both altitudes.

Optical sensors involve new reflectivity and absorptivity mechanisms, which do not match simply to those familiar from UHF radars, so their interpretation involves complications. Limited experiments indicate that optical sensors see pieces of debris that radars do not see, but miss objects that radars track readily—and vice versa. Currently, there are factor-of-two differences between optical and radar measurements of 10 to 20 cm objects, so optical measurements cannot be used to resolve the radar issues discussed above. After the upgrades and calibration, optical sensors should be able to make a major contribution to understanding the size and shape of the small particles of concern for manned space flight.

Correlating radar and optical observations, let alone resolving the issues above, is a difficult technical task that will probably require a long-term effort by a team of competent specialists in a center of excellence. They will need to be knowledgeable in theory and experiment—in the laboratory and in space. As only the Air Force has the full suite of radar and optical sensors and the background in space physics needed to address this task, it is essential that the Air Force lead the effort. It is not clear that such a center of expertise exists within the Air Force today; it will probably have to be created.

The Study briefly reviewed NASA's program for actively clearing debris with lasers, which is still under definition.¹³ The large radars needed to detect and track ≈ 1 cm debris were not included in the program. The laser is roughly specified, but at the cost at which large operational lasers have been built, a system for clearing at the $> 1,000$ km altitudes of concern could cost $\approx \$1B$. The program has significant risk and expense, but they appear to be less than those of alternative mitigation measures—such as tighter restrictions on fragmentation or the prompt deorbiting of spacecraft and rockets at end of life—that are already under consideration. However, on the basis of the data and analysis below, it is not clear that active clearing is needed, so the Study did not evaluate it further.

Space Station and Shuttle altitudes. The Study reviewed impact rate data at Space Station and Shuttle operating altitudes of 300-500 km, where the MIT Lincoln Laboratory Haystack x-band radar should give the most reliable data—particularly on the > 1 cm particles that are of greatest concern to manned spacecraft because of their ability to penetrate shields. When the Study first reviewed the data, it noted that the Orbital Debris Engineering Model (ODEM) 1989 model used to represent it was about an order of magnitude higher than the vertical staring (90°)

data through 1993. The measured flux of $\approx 2 \times 10^{-7}/\text{m}^2\text{-yr}$ gives an impact rate of $2\pi \times 10^{-7}/\text{m}^2\text{-yr} \times 5,000 \text{ m}^2 \approx 3 \times 10^{-3}/\text{yr}$, on a 5,000 m^2 Space Station—where the factor of π is for NASA's normalization to total rather than projected area in Figs. 5.¹⁴ That gives an impact probability of 3% in a decade of operation, which might not justify additional shielding.

Given the discrepancy between the data and model, the Study suggested it might be best for NASA to ignore the model and use Haystack data directly to estimate environments. NASA scientists then indicated that "An error was found in...the computer program which used the NASA model to predict what Haystack should see...all of the NASA model predicted count rates are too high, especially those at lower altitudes...these effects could produce a residual uncertainty "somewhere between a factor of 2 and factor of 11 difference between the model and measurements..."¹⁵ The top curve on Fig. 5 shows the ODEM 1989; the bottom curve shows the resulting ODEM 1996,¹⁶ which reduces the fluxes at all sizes $< 1 \text{ m}$ about an order of magnitude from ODEM 1989, as recommended by the Study. The new Haystack report does not give any data or models for the altitudes below 500 km of interest to manned systems, but the data from previous years cited shows that for vertical staring, the $> 1 \text{ cm}$ flux at 350-450 km is about an order of magnitude below that at 450-550 km shown in Fig. 5. Decreasing the $\approx 2 \times 10^{-6}/\text{m}^2\text{-yr}$ flux shown by a factor of 10 again gives an impact rate of $\approx 3 \times 10^{-3}/\text{yr}$ on Space Station, or one collision in about 300 years. The Space Station is instead being "armored against the 1-in-77 chance that it will be hit by an object larger than a centimeter."¹⁷

NASA apparently communicates the Space Station shielding requirements to the shielding community through the ODEM rather than through the data, so the Study inquired whether this 10-fold reduction had reduced the shielding requirements for Space Station. Modifications would be appropriate in the NASA *Safety Report*, the National Research Council's *Orbital Debris*, the Office of Science and Technology Policy (OSTP) *Interagency Report on Orbital Debris*, the Interagency Study based on them, and the UN deliberations. NASA's response that "impact rates are higher for smaller particles," so they were "shifting emphasis to millimeter sized objects, for which shielding is less demanding" was given by the same person cited in the previous paragraph.

Shielding of manned systems is not a direct concern of military space, and it is shown below that the shielding of unmanned satellites is a minor concern at present. It has also been shown that there is essentially no coupling between debris growth at 1,000 km and the environment at 400 km.¹⁸ Thus, the issues for manned space decouple from those for unmanned space, and it would be appropriate for NASA to pursue the former and the DoD the latter—unfettered by NASA uncertainties over low altitude environments. Thus, environments at manned space altitudes appear not to be a serious consideration for the DoD, and they were not pursued further than the actions above.

Radar interpretation. Haystack data are ambiguous because there are large resonances

in debris radar cross sections in the 0.5 to 5 cm region of interest. Figure 6 shows the resonances as functions of wavelength for the simplest case, a perfectly reflecting sphere, which is one of the few objects for which the cross section can be predicted. Given a radar return πa^2 , it is indeterminate whether the particle diameter is 0.5, 1.5, or 2 times λ/π . For x-band, $\lambda \approx 3$ cm, so it is ambiguous whether the particle diameter is ≈ 0.5 , 1.5, or 2 cm. For a return consistent with a cross section of $2\pi a^2$, it would be ambiguous whether the particle diameter was from 0.6 to 10 λ/π . Debris particle cross sections change that much on rotation by a few degrees because of their asymmetric shape and the resulting strong angular dependent of their scattering cross section.

NASA infers particle sizes using laboratory measurements of the returns from a selected collection of objects over many orientations, which averages out the phase information in their scattering cross sections shown in Fig. 6. Those averages are misleading in attempting to interpret the return from an on orbit particle, because neither its cross section nor its orientation are known, and rotation by a few degrees can cause the return to vary by orders of magnitude. Thus, similar returns could be generated by particles of greatly differing sizes at different orientations, which makes the determination of size from single observations indeterminate. This problem is caused by the loss of phase information, it cannot be compensated by practical amounts of observation. Haystack's narrow samples few particles even after years of observation; the chance of seeing one at multiple angles is smaller still.¹⁹ Thus, diameter measurements appear ambiguous by factors of 2-4 at small sizes.

A correct, unambiguous inversion of the return signals is needed for more than order-of-magnitude estimates of the particle densities at small sizes. It would be appropriate for AFSPC to support a fundamental study of unambiguous inversion of the return signals from high frequency radars. It should treat the scattering properties of realistic debris distributions deterministically and statistically, produce algorithms of known variance that retain phase information for the inversion of radar returns, and compare those results with existing or additional Haystack data. If successful, the results should then be used with Doppler and other information to separate man-made debris from the natural meteoroid background. Improved algorithms should be capable of giving unambiguous measurement of the fraction of > 1 cm objects that are man-made and controllable.

800-1,000 km impact rate. Figure 7 shows that at the altitudes of meteorological, remote sensing, and communications satellites, Haystack data roughly agree with the NASA ODEM model for particles > 1 cm.²⁰ The flux there is $\approx 3 \times 10^{-5}/\text{m}^2\text{-yr}$, which gives an impact rate of $\approx 3\pi \times 10^{-5}/\text{m}^2\text{-yr} \times 40 \text{ m}^2 = 4 \times 10^{-3}/\text{year}$ on a 40 m^2 satellite. That would reduce its ≈ 10 year expected operational life by a few percent, which is small compared to other operational factors considered in its amortization. NASA has suggested that the debris density could increase 10-fold in the next century, which would decrease the satellite's expected lifetime $\approx 5\%$.

A $4 \times 10^{-3}/\text{year}$ impact rate would give 0.4 collisions per year with a 100 satellite

constellation, or 4 collisions per year with a 1,000 satellite constellation. Collisions with ≈ 1 cm particles would only damage a satellite, with vulnerability cross sections smaller than the geometric values above. Available data indicate that collisions between few cm particles and satellites would not produce significant numbers of additional particles or initiate a cascade, only reduce the satellite's lifetime, as discussed above, in a manner independent of the size of the constellation.

For > 10 cm particles that could produce significant numbers of secondary particles in collisions, the Haystack data is a factor of 3 to 10 below the NASA 850-950 km ODEM model,²¹ which would give an impact rate of $\approx \pi \times 10^{-7} / \text{m}^2 \cdot \text{yr} \times 40 \text{ m}^2 \approx 10^{-5} / \text{yr}$ on a 40 m^2 satellite, or ≈ 0.01 collisions per year on a 1,000 satellite constellation. The data below indicate that such collisions produce ≈ 50 -80 particles per collision, so the constellation would produce ≈ 0.01 collisions/year $\times$ 50-80 particles/collision ≈ 0.5 -0.8 catalog fragments per year, which is small compared to orbital decay from the debris constellation. The fragments would be spread over an interval of several hundred kilometers in altitude, which is much larger than the spread of typical constellations. Thus, collisions of current or projected levels of debris with existing or proposed satellite constellations would not lead to cascading.

The overall agreement between debris impact predictions and data is not satisfactory. Haystack data, which should be the most precise for 1 to 10 cm debris, do not agree with the NASA models used to communicate impact environments to mitigators for the altitude and particle sizes for which agreement is significant. The data do not indicate a clear impact hazard at low or intermediate altitudes. They do not indicate a cascade at any altitude. On the basis of this data, current levels of debris do not represent a significant hazard to current or projected constellations, and should not cascade to levels that would represent a hazard to future space operations.

Launch rate is a principal determinant of the debris production rate. The number of spacecraft, rockets, associated objects, and fragments per launch have remained fairly stable over the last few decades, so if the launch rate is known, the total rate of inserting objects of various types can be estimated by a simple multiplication. Figure 8 shows the total launch rate over the history of the space program.²² Over the first decade it built to about 120 launches per year, where it remained until about 1980. Then it started to fall because of the reduction in the number of CIS launches, which actually started 5-10 years before the end of the Cold War. The result was a decrease in the global launch rate from 130/year in 1982 to 75/year by 1995, i.e., almost a factor of two in a little more than a decade.

The decrease in the launch rate to LEO was even larger. The total fell from about 110/year to 40/year, a factor of 2.8. Most of those launches were to orbits with perigees > 800 km. The number to perigees < 800 km, which would produce most of the collisions, fell from about 20/year to 5/year, a factor of 4—mostly over the last 5 years. A simple extrapolation of the trends of recent decades suggests a continued strong decrease, particularly to LEO. There is no basis in the

historical data to suggest a resumption of historically high launch rates of 120/year or more, let alone justification for assumptions of growth.

For useful projections, it is necessary to have an estimate of launch rate that is valid for at least several decades. Such projections are available in the form of recent studies that project launch rates for the Defense, Civil, and Commercial sectors. The Defense sector, which is the dominant sector at present, has been the most predictable historically because of its commitment to long-term missions and its enforcement of launch schedules to support them. There are two slightly different projections for DoD launch rates. That based on identified missions and payloads projects a decline of slightly more than 5%/yr over the next decade, falling to about 6 launches per year by 2005 from the current 11.²³ The Space Launch Modernization Study ("Moorman Study"), which takes a broader view of the Air Force's responsibilities for military missions and civil support, assumes a constant level of 30 government and 15 commercial launches per year to support the ELV development program.²⁴ The only military launch LEO indicated is DMSP, which involves a few launches per decade. Neither study predicts growth of military launches to LEO.

The civil sector is projected to increase to about 10 launches/year by 2000, although the payloads needed to do so are not specified. After that time it is expected to experience a decline similar to the DoD.²⁵ NASA's "Access to Space Study" carries a projection out to 2030 of a constant 15 NASA launches/year, 14 DoD launches per year, 5 commercial launches per year, plus a possible "growth" of 9 commercial launches per year.²⁶

The commercial sector reached a peak of 10 launches in 1995, which is roughly a stable launch rate for GEO communications systems. It does not appear possible to forecast far ahead for other segments of that sector with the exception of communication satellites. There are a number of proposed 100 to 1,000 satellite communication constellations, a few of which should survive to deployment, although they compete directly with emerging GEO and fiber systems. If deployed = 4 satellites per launcher, a 100 satellite constellation with 10 year lifetimes would add about 100 satellites / 4/launcher / 10 years = 2.5 launches per year, which would be a $\approx 2.5/70 \approx 3.5\%$ increase to the current rate in Fig. 8. Deployed = 2 per launcher, a 1,000 satellite constellation would add 1,000 satellites / 2/launcher / 10 years = 50 launches per year, which would be a $\approx 70\%$ increase. There is little danger of collisions between these satellites when active, and it is planned to deorbit them at end of life. Impacts by small and large objects are discussed above and are minor issues. The main issue is the cost and means of the disposition of the large satellites and boosters to deploy and refresh them, if required.

Apart from communication satellites, a reasonable prediction would appear to be a sharply decreasing launch rate to LEO. The most developed communication constellation would give enough growth through 2000 to roughly offset the decline in Defense. Thereafter, the commercial replacement rate would not match the Defense decline and the general shift to GEO, so the total

launch rate to LEO would decline. Given the uncertainty in commercial efforts, perhaps the best estimate is a change in growth rate between zero and -5%/yr, which is the range the Study used in analyses below. NASA typically assumes a fixed debris growth rate from historical launch rates that are about a factor of 2 larger than current rates, which produces correspondingly higher launch and fragmentation rates.

Orbits. The previous section discusses the total launch rate. It is useful to differentiate that total by the orbits to which those payloads are launched. Figure 8 shows the decrease in the overall launch rate, and gives some indication of the more rapid decrease in the launch rate to GEO. One reason for the rapid decrease is that many DoD, civil, and commercial payloads in the U.S. and abroad are shifting from LEO to GEO for operational advantages such as global coverage with fewer satellites. Figure 9 shows the fraction of successful launches to LEO and deep space.²⁷ The shift from LEO to deep space has been about constant and linear in time and is now approaching 50%. If that trend continues, in the future the launches to LEO will be a minority of payloads. Absent the communications constellations discussed above, the launch rate to LEO could fall to 10% or less of the historical rates of previous decades.

Figure 10 integrates this shift from LEO to GEO with the overall launch rate projections of the previous section to produce a composite LEO launch rate projection for the next century.²⁸ The top curve is for a 1000 satellite LEO constellation deployed two satellites per rocket; the bottom curve is for a 100 satellite constellation deployed four satellites per rocket, which is the nominal configuration for the most developed constellation. For the 1,000 satellite constellation, the launch rate gradually falls about 50% from the peak of the last decade, largely due to the shift of other launches from LEO to GEO. For the 100 satellite constellation, the launch rate falls over the next few decades to about 350/decade, which is $\approx 1/4$ the peak rate of the '80s, or $\approx 1/2$ the current rate. Only the large constellation would support a large launch rate. It is unlikely that more than one such constellation would be launched, as communications generally goes to the system that deploys first. Each time a payload is launched to GEO, it leaves a geosynchronous transfer orbit (GTO) stage on its way, which generally doesn't decay for a number of decades. However, those GTO stages spend most of their time above LEO. Only the $\approx 5\%$ of their orbit they spend in LEO should be accounted there, as it is in the LEO catalog and collision calculations discussed below.

Debris sources. The major sources of space debris are rockets, payloads, operational items, and fragments from the explosion of rockets or spacecraft. The previous section discussed projected rates of insertion of spacecraft and rockets. The sections below discuss the explosion rate, collision rate, and decay rate, to arrive at predictions of the fragment production and cascade rates and their sensitivity to physical and model parameters. Most debris has been tracked since its birth, so its source is known, as shown in Table 1.

Table 1. Source of debris from prior deployments and explosions.

Source	Number	Percent	growth (%/yr)
Active payloads	430	6	
Operational debris	1000	13	1.1
Rocket bodies	1300	18	4.8
Inactive payloads	1570	22	4.6
<u>Fragments</u>	<u>3100</u>	<u>41</u>	<u>1.1</u>
Total	7400	100%	2.7

The number and percent are for the debris particles now in orbit.²⁹ The growth rates for each component are compounded over the last 20 years.³⁰ The growth of spacecraft is assigned to inactive payloads, since each satellite has only a finite active phase before it joins the inactive inventory, and the distinction between active and inactive payloads is not essential for treatments of debris. Active and inactive payloads constitute almost a third of the total, as does the sum of the rocket bodies and operational debris. The remaining 40% is fragments from rocket explosions. Table 1 gives the total debris at all altitudes. There are about 500 spacecraft and 1,000 fragments above LEO; the total number of debris objects in LEO is about 5,300.

Figure 11 shows the LEO fragment source distribution as a function of explosion altitude and fragments per explosion. While a large number of explosions produce few or no fragments, a number also produce large numbers, such as the explosions at 700 to 1,000 km, which produced on the order of 200 fragments apiece, and the two large explosions at about 700 km that produce about 450 each. The fragments at 1,450 are produced by a number of explosions, each of which produced a modest number of fragments. There have been no large explosions above 1,000 km, which is the main region of concern for long-term stability, which is apparently due to the lack of utilization of those altitudes.

Fragments are the largest component of Table 1. There have been about 120 fragmentations in the $\approx 3,500$ launches to date, which gives a probability of explosion of $\approx 3.4\%$ per launch. Those explosions produced $\approx 8,100$ fragments, about 7,300 in LEO, which gives $\approx 7,300/3,500 \approx 2.1$ fragments per launch or $7,300/120 \approx 60$ fragments per explosion. About 3,100 fragments remain in orbit, $\approx 2,700$ in LEO. The number of fragments per explosion has varied widely—about 25% of the fragments were produced by the 10 largest explosions—but on average, the 60 objects/explosion $\times 3.4\% = 2$ objects/launch from launches that explode is comparable to the ≈ 1 rocket + 1 operational debris + 1.3 payload ≈ 3.3 objects/launch from the 97% that don't.

Figure 12 shows that at present, rocket bodies, payloads, operational debris, and fragments each constitute a significant fraction of the total debris. In the future, rocket bodies and payloads should track the reduced launch rates discussed above. Measures that have already been

implemented have reduced operational debris to about 1 piece per launch, so it is growing slowly. That also seems to be the case for fragments from explosions. Although they the dominant component of debris today, they are now growing slowly, if at all. Their value of $\sim 3,000$ is about the same today as it was 20 years ago. It may be that the combination of the altitudes at which they are produced and the high drag of these smaller objects have produced a rough balance between production and decay. If so, as launch rates fall, the number of fragments and operational debris objects should fall approximately proportionally.

The top curve in Figure 13 presents the total number of objects in LEO, which has remained at about 6,000 for the last two decades. The other two curves break the total in to those with perigees < 800 km and those with perigees > 800 km. The former orbits have relatively high drag; thus, when the CIS began to reduce its launch rate in the early 1980s, their population began to fall. The reduction to date is about a factor of two, which is comparable to the reduction in launch rate to those orbits shown in Fig. 8. The latter for perigees > 800 km continue to increase, even though their launch rates in Fig. 8 fall as rapidly as those to the lower orbits. The objects at higher altitudes are affected less by drag, so the objects launched to those orbits accumulate there.

The rate of explosions on orbit has been uneven. At altitudes such as 1,000 km, there have been only a few explosions, separated by intervals from years to decades. The intervals appear random and relatively insensitive to the policies discussed below. Some explosions have involved U.S. launchers, which now have the technology to eliminate them. Others have involved CIS launches of satellites that are no longer needed, or that no longer need to be launched to the most bothersome LEO orbits. Thus, it is likely that the number of explosions will decrease with time, independent of further positive actions. As to the other sources of debris, operational items are reduced by mature space programs, although that may not be the case for new users of space. If fragmentation and operational debris could be reduced, the number of payloads and rockets launched could perhaps remain at current levels without producing overall debris growth.

U.S. debris policy. In 1988 the Reagan administration approved a policy including the statement that "all space sectors will seek to minimize creation of space debris."³¹ Several agencies have implementing policies. NASA has a policy of burning boosters to completion and of "limiting the generation of orbital debris consistent with mission requirements and cost effectiveness." NOAA boosts some spent satellites above GEO at end of life. DOT establishes regulations for launch safety. The DoD Space Policy of February 1987 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."³² The DoD has had little problem with fragmentation since its decision to burn rocket fuels to completion several decades ago, although other civil and foreign agencies continued to experience large fragmentations.

DoD and NASA policies have been in effect for several decades. On the surface, they have been successful, in that the amount of debris in space has remained essentially constant.³³ However, the policies actually may have had little effect. Table 1 and Fig. 12 show that fragments and operational debris, the components that should be affected by these policies, have grown little over the last 20 years. They saturated at effectively their current values in about 1975, about a decade before the U.S. policies went into effect. Growth since that time has largely been in rockets and payloads, which are not restricted by the policy. This shift in debris growth from fragment to payloads and rockets is little noted, but must be a consideration in any proposed changes in space policy, which should logically evolve from preventing the growth of fragments to preventing that of large, intact objects, for which the measures required are different and more expensive.

Eliminating fragmentation altogether would only decrease the source rate $= 2/(2 + 3.3) = 38\%$ in the near term—less in the long. Nevertheless, catalog fragments are a significant fraction of the total number of objects that could participate in catastrophic collisions, so their reduction remains of value—particularly since alternative measures of mitigation, such as deorbiting payloads and boosters, involve significant mass and cost penalties. Thus, it is appropriate to minimize fragmentation, but that cannot be done unilaterally. To date about 75% of the fragmentations have been of CIS systems, although the total number of fragments has been more evenly divided between the CIS and U.S.

Explosions. The two main sources of data on explosions are a large-scale field experiment and about 120 explosions on orbit. The Study reviewed their data on debris size, areal density, and debris velocity. The one large-scale ground explosion experiment was an intentional explosion of an Atlas 24D booster at the U.S. Army Aberdeen Proving Ground in 1961.³⁴ The 20 m x 3 m diameter booster had a mass of 1787 kg, of which 1254 kg was collected. Figure 14 shows that the 1,337 pieces collected ranged from about 0.5 gm to 450 kg. The straight line with slope $1/\text{mass}^{0.7}$ is a fit to the cumulative distribution of fragments over mass.³⁵ It lies above the data for debris masses < 0.1 kg, which means it over predicts small fragments. However, for catalog objects, which have masses greater than about 1 kg, this discrepancy is not a concern.

For masses between 40 and 200 kg, the fit lies above the data by factors of two to three; thus, it significantly overestimates the number of large objects, which are likely participate in further collisions and produce large numbers of particles. This "missing" mass apparently resides in uncollected small particles, which could not participate in cascading collisions. There are about 150 particles > 1 kg, which is arguably a relevant number for scaling, although it is specific to this booster and fuel loading. After 35 years, there is apparently still no fundamental understanding of how the particle distribution would scale to other conditions. However, this number is roughly consistent with model predictions and the on-orbit average of 60 fragments per explosion.

The Study reviewed the Atlas data on fragment areal density—i.e., mass per unit area or

"ballistic coefficient"—which determines the rate of orbital decay of fragments. Figure 15 shows average size as a function of mass. Areal densities range from $\approx 0.01 \text{ kg}/(0.1 \text{ m})^2 \approx 1 \text{ kg}/\text{m}^2$ at 0.01 kg to $10 \text{ kg}/(1 \text{ m})^2 \approx 10 \text{ kg}/\text{m}^2$ at 10 kg, all of which are small enough to produce significant drag.³⁶ The areal density scales roughly as $\text{mass}^{1/3}$, which extends to larger areal densities at larger masses, although the data are sparse and the statistics are poor there.

The Study also examined the velocity dependence of fragments from the Atlas explosion as a function of mass, which is shown in Figure 16. The velocities of $\approx 3 \text{ kg}$ fragments approach 0.4 km/s. The velocities decrease with size roughly $1/\sqrt{\text{mass}}$, as shown by the trend line; however, the spread in velocity is about an order of magnitude at every mass, so catalog fragment velocities range from 1 to 500 m/s.³⁷ The spread of fragments in space is proportional to this velocity, so this uncertainty means the subsequent density of fragments is uncertain by a like amount.

As noted above, the 120 explosions to date produced about 60 LEO catalog fragments per explosion at a rate of $\approx 3.5/\text{yr}$, which has roughly constant over time. There may have been fragments that were too small for UHF radars to see, but their omission from the catalog is not a deficiency for the analysis below, as experiments indicate that particles too small to see with UHF radars are also too small to produce large numbers of particles in collisions. The number of objects associated with a given explosion increases with time, since continuing observation gradually detects and associates more fragments. However, that appears to be a modest effect, predictable, and largely included in the average of 60 fragments per explosion.

Observations of on-orbit fragmentations do not measure mass or area directly; they can at best measure object number, observe radar cross section (RCS), and infer drag. Radar object and RCS measurements are the basis for the catalog shown in Figs. 1-3. The measurement of the change of an object's trajectory by drag is an independent kinematic measurement that determines the ratio of fragment mass to area, which can be multiplied by its measured RCS to estimate fragment mass.³⁸ Figure 17 shows a area per unit mass probability histogram for the fragments from the 1981 Landsat 3 explosion at 900 km. Most of the values range from 0.2 to $20 \text{ kg}/\text{m}^2$, although there are spikes to $\approx 300 \text{ kg}/\text{m}^2$. About 20% of the ballistic coefficients inferred were negative, so even Landsat 3 trajectories, which are among the cleaner ones studied, were too noisy to infer precise ballistic coefficients.³⁹ However, they do give a distribution of areal densities from a typical explosions on orbit in rough agreement with that in Fig. 15 from Atlas.

Trajectory measurements also provide direct information on fragment velocities. Figure 18 gives the "Gabbard diagram," or plot of fragment period versus apogee and perigee, soon after the Landsat 3 rocket body fragmentation.⁴⁰ These parameters can be determined as functions of debris velocity through astrodynamic calculations that can be inverted to estimate fragment velocities from observed parameters, which the Study did for a few dozen of the largest explosions. The inferred debris velocities typically ranged from 0.1 to 0.3 km/s; the Landsat 3 explosion is fit by a fragment

velocity of about 0.2 km/s. In addition to these routine observations, there are more careful observations of a few intentional fragmentation tests, which give velocity distributions of kilogram or greater fragments ranging from 10 to 2,000 m/s, with little correlation between velocity and mass,⁴¹ as seen in the Atlas data of Fig. 16.

Figure 19 shows NASA's fit to this data. For a nominal minimum catalog object size of 10 cm, the peak velocity is about 0.2 km/s. The model has a very sharp peak at that velocity, so there are no particles at velocities 30% larger.⁴² That contrasts with the Atlas data, which has a significant fraction of the particles larger than a kilogram moving at velocities of ≥ 0.1 km/s. Thus, the NASA model confines debris to a smaller altitude interval than does the data.

The data on 120 on-orbit explosions yield a stable average of about 60 catalog fragments per explosion, roughly constant with time. The ground test gave about 150 fragments. Thus, there seems to be a basis for using a value of 60-150 fragments per explosion in analyses. NASA analyses assume 300 fragments per explosion,⁴³ which is a factor of two to five larger, and approaches the maximum number of fragments ever observed in Fig. 11. There is no basis in the data or analysis above for substituting the maximum for the average; the only basis given for the substitution by NASA is "conservatism." However, substituting 300 fragments per collision in the 120 historical explosions would produce $\approx 36,000$ fragments, which is a factor of $\approx 300 \times 120 / 8000 \approx 4.5$ more fragments than have actually been produced—and a factor of $300 \times 120 / 24,000 \approx 50\%$ more debris objects than have ever been cataloged from all sources. AFSPC uses conservative, historical explosion rates and numbers of fragments per explosion.

Collisions. The Study produced an independent estimate of the debris collision rate by performing the appropriate integrals over the debris distribution in Fig. 2. The result is shown in Fig. 20, which gives the differential and integral collision rates as functions of altitude. The bottom curve is the differential rate, i.e., the rate of collision in a 100 km altitude bin. It increases linearly with altitude from about 450 to 850 km. It rises more rapidly to 950 km, after which it falls sharply, with a small additional contribution at 1,450 km. The upper curve is the integral of the collision rate, which rises quadratically with altitude to about 950 km, by which it reaches about 90% of its asymptotic value of $\approx 0.05/\text{yr}$ —the same value cited by NASA.⁴⁴

There is little experimental evidence to which to compare these collision rates. Recently, there is thought to have been a collision between a small French Cerise satellite and a decaying fragment from Spot 1.⁴⁵ With the above collision rate of $\approx 0.05/\text{yr}$, the probability of 35 years of linearly growing space activity with no collisions would be $\approx \exp(-0.025/\text{yr} \times 35 \text{ yr}) \approx 0.42$, so such a collision would not be unlikely. However, the rates calculated in Fig. 20 are dominated by large objects, while the reported collision involved two small objects. If so, it was an *a priori* unlikely event.

At a given altitude, the collision rate is proportional to the total object area there. The area of

an object is roughly proportional to its mass. The total mass is the sum of the object masses. Thus, the mass at a given altitude is related to the collision rate there, and the total mass on orbit is related to the total collision rate. This relationship can be quantified approximately. The calculation that produces Fig. 20 also estimates the total area on orbit to be about $16,000 \text{ m}^2$. According to Fig. 12, most of that is in a $\approx 2:1$ mix of payloads and rockets, which have typical areal densities of 200 and 70 kg/m^2 , respectively.⁴⁶ That gives an average areal density of $\approx 140 \text{ kg/m}^2$, and a total mass of $\approx 16,000 \text{ m}^2 \times 140 \text{ kg/m}^2 = 2,150$ tons. That value agrees to within about 10% with the value shown in Fig. 21, which is NASA's estimate of mass on orbit from an inventory of launches and decays.⁴⁷ The total mass closely tracks the spacecraft and rocket body curves of Fig. 12, because those objects contain most of the mass and resist orbital decay. The difference between this estimate and Fig. 21 is a rough indication of the likely error in each, as both are ultimately tied to AFSPC's catalog for object parameters, and AFSPC radars cannot measure mass and its catalog does not have an accurate approximation to it.

Figure 20 results from performing integrals over the debris distribution $n(A,z)$ in Fig. 2, which is the number of objects with areas between A and $A + dA$ within a 100 km altitude bin at altitude z . If an object has area A , its diameter is $\approx \sqrt{A}$, so the geometric collision cross section of objects with areas A and A' is $\approx (\sqrt{A} + \sqrt{A'})^2$. If their relative velocity is v , their collision rate is proportional to $n(A)n(A')(\sqrt{A} + \sqrt{A'})^2 v$, where the dependence of n on z is suppressed. The collision rate of objects of all sizes is proportional to $\int dA \int dA' n(A)n(A')(\sqrt{A} + \sqrt{A'})^2 v$. While it can be evaluated without further approximation, collisions usually involve the flux of smaller particles with the area of the larger objects, so the two areas are dissimilar. Thus, the integral can be approximated as $\approx \int dA \int dA' n(A)n(A')(A + A')v = 2 \int dA n(A) \int dA' n(A') A' = N(z)\Sigma(z)$, where $N(z)$ is the total number of catalog particles at z and $\Sigma(z)$ is their total area. This result shows that the rate of collisions depends largely on the impacts of the numerous small objects, which dominate N , on the rare but large intact objects, which dominate $\Sigma(z)$. Thus, both the flux of fragments, whose growth has saturated, according to Fig. 12, and the area of the large objects, whose growth has not, not in Fig. 21, are important in calculating collision rates.

The collision rate is computed directly from catalog areas; the mass in orbit is not used, or even useful in that calculation. For mass on orbit is useful in providing an integral cross check on the total area in orbit; however, that is measured directly. Moreover, the mass on orbit is only as useful as the correlation of mass and area, which is indirect. A further observation is that the collision rate itself is not particularly useful except as a cross check between estimates. It involves impacts between particles of all sizes. Some are catastrophic, i.e., produce many fragments; most are not. It is only collisions that can produce numerous fragments that are of interest, and they are computed in a different manner described below. The connection between the two calculations is at best indirect. However, the overall uncertainties in catalog collision rate and mass on orbit appear

to be on the order of 10%, which would at most impact other estimates to a like amount, which is not critical for this Study.

Fragment production. The Study performed an independent evaluation of the catalog debris fragmentation rate, producing the result shown in Fig. 22.⁴⁸ The bottom curve is the differential production rate; the top curve is its integral over altitude. The two curves resemble the collision rate of Fig. 20, except that the differential curve has a peak at about 350 km. However, the fragments born at low altitudes do not survive long enough to collide, so that difference is unessential. The integral curve again sums to about 90% of its ≈ 2.7 fragment/year asymptote by about 950 km. At 950 km, the fragment production rate is $\approx 0.75/\text{yr}$. Figure 1 indicates that there are $\approx 1,000$ particles in a 100 km bin there. For them to double by collisions would take $\approx 1,000$ particles / 0.75 particles/yr $\approx 1,300$ years, which is comparable to the fragments' orbital decay times. The production rate falls sharply above 1,000 km, so growth would be slower there.

The ratio of the integral fragment production rate to the $0.05/\text{yr}$ collision rate of the previous section gives ≈ 2.7 fragment/year / 0.05 collision/year ≈ 55 fragments/collision for nominal parameters, which is modest compared to other estimates. The number of fragments per collision does depend on a few parameters, which have been measured in a series of DoD railgun tests. The railgun tests were typically performed at velocities ≈ 6 km/s with ≈ 0.1 kg impactors hitting scaled 20-30 kg targets. About a dozen tests are both relevant and usefully diagnosed.⁴⁹ Their results are typically interpreted with a one-parameter fit $B'(M/m)^B$ to the cumulative number of particles with mass larger than m , where M is the mass of the impactor plus target, B is an empirical exponent determined by matching the data, and $B' = 1/B - 1$ by conservation of mass.

Figure 23 shows the data from a typical test, Satellite Orbital Debris Characterization Impact Test (SOCIT) 3 at Arnold EDC, which involved a 0.15 kg, 6.1 km/s impactor on a mock up Oscar satellite weighing 29.6 kg, of which 15.6 kg was collected. The collision produced about 100 collectible particles, about 50 of which were larger than 0.1 kg. The straight line fit to the data gives $B = 0.65$ and $B' = 0.53$. The full series of experiments gave $B = 0.61 \pm 0.08$. The average fragment size as a function of fragment mass has a slope of about $1/4$, which is in rough agreement with that from the Atlas data of Fig. 15. The velocity data has greater scatter and no more correlation with mass than the Atlas data of Fig. 16.⁵⁰

The average value of $B = 0.61$, and its experimental range is from 0.53 to 0.7, but in Fig. 24, B is varied from 0.2 to 1. The number of fragments per collision is smaller at smaller B . By 0.7, the maximum value consistent with experiments, the number increases to about 70 fragments/collision. Increasing B to larger values of B produce larger numbers of fragments, but is not consistent with the experimental data base. A value of 0.85 produces about 90 fragments/collision. For larger values of B , the number drops sharply. As noted above, the number and distribution of fragments from the Atlas test was broadly similar to those from the

railgun tests, leading to the suggestion that large explosions be used as a surrogate for large collisions. The value of B from the Atlas test was about 0.69, which would produce about 70 fragments/collision. Thus, within the framework of the model used to analyze DoD tests, explosions would not on average produce more fragments than collisions.

There is little on-orbit data for comparison. The one reported collision of a small satellite with a decaying fragment is thought to have produced only one fragment, whereas the laboratory-derived scaling results above would have predicted several dozen fragments. It is argued that the collision may have severed a boom, which became that additional object.

The Study's catalog-derived value of ~ 55 catalog fragments/collision is in agreement with analytic⁵¹ and numerical⁵² estimates, but is not in agreement with NASA's analyses, which use an estimate of 480 fragments/collision.⁵³ Those studies outline calculations that parallel those above leading to Fig. 22. They also produce an average of "1,600 kg of fragments" per collision, which that is close to the value underlying Fig. 22,⁵⁴ but then simply state "an average collision would produce about 480 fragments larger than 10 cm..." without justification.⁵⁵ According to Fig. 24, there is no value of B that could produce that many fragments; using a value of 0.85 would produce at most about 90, which would leave a discrepancy of a factor of five. This discrepancy was discussed in with NASA scientists, who did not disagree with this analysis or with Study estimates of collisional doubling times. They only stated that their 480 particles per collision is a "conservative" estimate.⁵⁶ NASA apparently uses the *maximum* number of particles observed from *explosions* as a substitute for the *average* number of fragments per *collision* in its analyses, which overestimates the number of catalogue fragments per collision by an order of magnitude relative to theory and laboratory, field, and space experiments.^{57,58}

The fragment production rate is related to the collision rate of the previous section. The collision rate between objects with areas A and A' is $n(A)n(A')(\sqrt{A} + \sqrt{A'})^2 v$, so their fragment production rate is $\sim B'(M/m)^{Bs} n(A)n(A')(A + A')v \sim B'[(A+A')/C]^{Bs} n(A)n(A')(A + A')v$, where C is the area of the smallest catalog fragments and it is assumed that $m = KA^s$, where K is constant and $s = 1.1$.⁵⁹ For target area $A \gg$ impactor area A' , the rate of production of fragments by objects of all sizes is proportional to $B'/C^{Bs} \int dA n(A) A^{(1+B_s)} \int_{fA}^A dA' n(A')$. For $B_s = 0$, this resembles the integral for the collision rate; however, there is an essential difference. The integral over A' is only carried out over areas from fA to A , where $f \sim 10^{-3}$ is the minimum ratio of impactor to target mass that can cause a catastrophic collision determined from railgun tests.⁶⁰ This limit filters out the impacts of numerous small particles, which reduces the effective collision rate. For that reason, the catastrophic collisions that produce numerous particles are less sensitive to the flux of small particles than the unconstrained collision rate, and much more sensitive to the number of large objects.

The greatest impact of this filtering is the elimination of particle production by the impacts

of the smallest catalog particles on target objects a factor of $\approx 1/\sqrt{f} = 30$ times larger. At 500-1,000 km, the AFSPC catalog falls off rapidly for objects larger than ≈ 3 m, so this filtering mostly affects particles smaller than $3 \text{ m} / 30 \approx 0.1 \text{ m}$. However, Fig. 2 shows that the catalog contains relatively few particles of that size. Thus, the inclusion or exclusion of the filtering of small objects has little impact on calculations with the AFSPC catalog. However, there are sensitivities to the catalog used. Figure 4 compares the AFSPC (SSN) and Evolve catalogs. At 950 km, which is the altitude of maximum density according to Fig. 1 and of maximum fragment production according to Fig. 22, the Evolve catalog > 10 cm density is larger than that from the SSN by a factor of 2-4. Thus, the inclusion or exclusion of the flux of small catalog particles would change the fragment production rate by a like amount by converting every catalog collision into a catastrophic collision. However, that shift would also increase the unconstrained collision rate by a like amount, so their ratio, which gives the number of fragments per collision should change little.

Because of the relationship between the integrals for the collision and fragmentation rates it is possible to calculate them with the same model, so that they can be calculated consistently for any given inputs, which was done in the Study. That means switching between the calculation of the collision rates of Fig. 20 and the fragment production rates of Fig. 22 only involved the change of one parameter, B , which was then varied continuously to provide the sensitivity analysis of Fig. 24, which minimized the possibility of error in the calculation of any of the three.

NASA characterizes its substitution of 480 for 55 fragments per collision as conservative. However, it seems inappropriate to make a replacement of that magnitude without justification or documentation. While there is no basis in data or analysis for replacing the average number of fragments per collision with the maximum number of fragments per explosion, doing so would be acceptable as an analytic excursion, if identified as such. However, it would appear appropriate for NASA to calculate and provided their estimates for nominal parameters as well. This factor of ≈ 9 conservatism in collisional fragment production is multiplicative with the factor of 5 in fragment production by explosions, because explosions and collisions are successive, independent steps towards cascading. Thus, the overall conservatism is apparently a factor of $\approx 5 \times 9 = 45$.

Fragment trajectories. The Study compared AFSPC and NASA treatments of the distribution of fragments over orbits. As the one reported collision produced only one fragment, the Study used explosions as a surrogate for both explosions and collisions, on the basis that both appear to involve largely isotropic fragment distributions and velocities. It confirmed that the catalog of fragments from known explosions decays to the debris distribution observed at present. Fig. 25 compares source catalog to the currently surviving fragment distribution. The Study tested AFSPC and NASA catalogs explosion locations for consistency, generated a distribution of the fragments and trajectories for each explosion, averaged the initial distributions to produce the "catalog" distribution, propagated them forward in time, and averaged the results to produce the

"remaining" fragment densities at the present time. The source catalog is fairly from ≈ 200 km to 1,000 km; thus, a roughly equal number of fragments has been produced in each altitude interval. The "remaining" distribution falls off sharply at altitudes below $\approx 1,000$ km due to orbital decay.

The bottom curve of Fig. 25 shows the distribution of the fragments remaining at present, which is similar to the catalog at high altitudes, but strongly attenuated by drag at low altitudes. The "remaining" distribution resembles the total debris distribution of Figs. 1, although according to Table 1, fragments are only about 40% of the total debris. It is shown below that the models used by the Study and AFSPC propagate the catalog to this remaining distribution. Comparison results from NASA models were not available to the Study.

This comparison roughly bounded the level of fidelity of orbital mechanics models needed to usefully model debris growth or decay. Figure 26 shows a coarsely zoned decomposition of the "remaining" distribution into its main components: particles accelerated forward parallel to the target object's trajectory (p+), particles accelerated anti-parallel (backwards) to the object's original trajectory (p-), particles accelerated locally upward (n+) and downward (n-), and those scattered to the side (init), which change inclination but retain their initial energy. The distribution above 1,000 km is dominated by p+ fragments accelerated in explosions at lower altitudes, which largely fill what would otherwise be a hole in the fragment source between 1,000 and 1,400 km. The distribution below 800 km is dominated by back scattered p- fragments decelerated from higher altitudes. The n and initial components show less altitude averaging. Improper treatment of the p+ and p- components would fundamentally alter the remaining distribution. AFSPC incorporates this spectrum of fragment trajectories in its standard calculations.⁶¹ The Study did not explicitly evaluate the models used by NASA for this purpose, as they are not documented in the literature to the level required. It would be useful to performed such a comparison in the future.

Figure 25 uses an average fragment velocity of 0.2 km/s. It is possible to infer the approximate debris velocity for each of the ≈ 100 LEO explosions from their Gabbard plots, as was done in Fig. 18 for Landsat 3. Instead, the Study checked the plots for the largest explosions that inject significant numbers of fragments at high altitudes. They typically have average debris velocities from ≈ 0.1 to 0.4 m/s. These variations have 2- to 4-fold impacts on the distribution of debris from individual explosions or collisions. The higher velocities distribute the debris over a wider range of altitudes, reducing the concentration at the event altitude and smoothing the overall distribution. Even the initial distribution in Fig. 25 shows considerable averaging over intervals of 100-200 km relative to the unaveraged fragment sources in Fig. 11. AFSPC measures and uses the actual explosion data from radar measurements in its calculations. Figure 19 indicates that NASA uses a maximum catalog velocity of ≈ 0.2 km/s for predictions.

Orbital decay. The Study tested the consistency of AFSPC and NASA treatments of orbital decay in the process of studying the propagation of catalog fragments to the present. It also

compared their models for spiral and eccentric decay, carefully for spiral decay; less thoroughly for eccentric decay, although adequately for the class of LEO orbits involved in fragmentation and collisions. NASA publications provided the basis for a more detailed comparison. Those important to their stability analyses describe the averaging of drag and collision rates over 100 km altitude bands for orbits of small eccentricity, which are used for estimates of cascade rates.⁶² Fragments are divided into two groups: those accelerated to larger semi-major axes, and those decelerated to smaller ones. For NASA's maximum 0.2 km/s increment, the accelerated particles increase their apogee by ≈ 100 km, where the air density is about a factor of three lower, which gives them a longer lifetime than that at the explosion altitude. The lifetime of particles scattered up from an explosion at 1,000 km is ≈ 700 years; the lifetime of those scattered down is ≈ 175 years. Under the assumption that half the particles are scattered up, the increase in the effective lifetime is large.

This model does illustrate the accumulation of the near-eccentric fragments, which are likely to survive long enough to collide, and it provides the basis for comparisons. The Study evaluated its approximations by using decay rates for circular orbits based on atmosphere and drag models due to Jacchia,⁶³ deduced decay rates for eccentric orbits from them⁶⁴ through an analysis by King-Hele.⁶⁵ Averaging these results over an assumed isotropic fragment angular distributions and the measured velocity and mass distributions provided effective lifetimes for all fragments.⁶⁶

The Study used Jacchia and King-Hele's results to estimate the average lifetimes $\langle T_+ \rangle$ and $\langle T_- \rangle$ of fragments scattered upward and downward, respectively.⁶⁷ For $z < 900$ km, $\langle T_+ \rangle \approx 3T_0$ and $\langle T_- \rangle \approx T_0/3$, and for $z > 900$ km, $\langle T_+ \rangle = \langle T_- \rangle \approx T_0$, where T_0 is the circular orbit decay time at altitude z . These results are in good agreement with those stated by JSC; thus, the foundations of the AFSPC and NASA decay models appear to agree at this level.⁶⁸

NASA used this result to calculate the fragment densities from a point source as $S = F' [\exp(-t/T_+) + \exp(-t/T_-)]/2$, where F' is the fragmentation rate. NASA further argued that for a constant F' , it is possible to integrate S over times $t \gg T_+, T_-$ to produce an "equilibrium spatial density" $\langle S \rangle = FT$, where $T = (T_+ + T_-)/2$.⁶⁹ The Study did not agree with NASA's use of this result in subsequent analyses. The actual value is $\langle S \rangle_{act} = F'[T_+[1 - \exp(-t/T_+)] + T_-[1 - \exp(-t/T_-)]]/2$. Figure 27 shows the ratio $\langle S \rangle_{act} / \langle S \rangle$ as a function of altitude and t . For $t = 0$, the ratio is zero for all z , because $\langle S \rangle_{act} = 0$ for all z , while NASA's $\langle S \rangle$ has already attained its asymptotic value. For small z , the ratio rises rapidly; it is about 0.9 by 25 years at 750 km. At 850 km, it reaches 0.9 in about 100 years. At 950 km, it takes more than 200 years to reach 0.9; in 100 years it only reaches 0.6. At 1,050 km the ratio reaches about 0.6 in 200 years. At 1,150 km it reaches about 0.5 in 200 years. Thus, even on time scales of centuries, it is difficult to accurately approximate the growth of the density, and time scales of several centuries are the appropriate time scales for concerns about debris growth. NASA uses the "equilibrium spatial density" $\langle S \rangle$ in stability analyses.⁷⁰ The corrected critical density for stability is inversely proportional to $\langle S \rangle_{act} /$

$\langle S \rangle$, so the factor of two error at 950 km at 100 years doubles the critical density, reversing the conclusion of the NASA analysis.

Debris growth. The results discussed in the previous section required the Study to develop relatively simple but accurate models of debris growth and decay, which it tested by accurately predicting the evolution of the LEO debris catalog to its current configuration. The predictions shown in Fig. 28 are from a two-component flux model, which treats the debris distribution at each altitude as a set of "fragments" smaller than 0.3 m^2 with an average areal density of 3 kg/m^2 and a set of large, intact objects of average cross section 10 m^2 with an average areal density of 150 kg/m^2 .⁷¹ The sources of the fragments and large objects are taken to be the yearly averages of the 24,000 debris objects cataloged to date, averaged over orbits and altitudes in the manner used to produce the collision and fragmentation rate calculations discussed above.

The calculated values are within about 5% of the two main peaks at 950 and 1,450 km in the AFSPC 1995 catalog, which contain most of the objects. That the 1,450 peak is largely "fragments" results from the definition used, which places the small 0.3 to 1 m^2 , intact objects in Fig. 2 into the fragment category. In the 950 km peak, the partition between the fragments, which have largely decayed, and the large objects, which have not, is consistent with the catalog. The number of large objects is consistent with the number currently on orbit.

The agreement between the sum of the fragments and large objects with the 1995 catalog is within 5-10% down to about 850 km. At lower altitudes the agreement is factor-of-two down to 350 km, where it improves again due to the large number of large objects. The discrepancy at 450-750 km is apparently due to the oversimplified treatment of eccentricities developed in the previous section. However, the particle densities at those altitudes are smaller than those at 850-950 km, where most collisions take place, and the atmospheric densities at 450-750 km are sufficiently high that fragments created by explosions or collisions there have relatively short lifetimes.

Figure 28 is for historical growth rates. If continued into the future, the debris distribution shown would essentially grow linearly, except that the 1,450 km peak would grow slightly faster due to the larger source and smaller decay of fragments there. Those factors would gradually shift the former to a peak of fragments and the latter to a peak of large objects. Figure 29 shows the growth of the fragment, large, and total object populations from the start of the space age at year 0, through the present at year 35, to 2160. The growth rate was relatively large up to the present. Through the end of this century the catalog would roughly double, for an average growth rate of about 1%/yr. It would roughly double again in the following century, for a growth rate of about 0.7%/yr. For the nominal rates of Fig. 22, such growth would involve little cascading in the next few centuries. The overall growth from the present to year 200 is about a factor of 4, which would increase the debris flux by a like amount. According to the discussion of the radar observations on Fig. 4, that appears to be about the level of uncertainty in the current small object environment.

The section on launch rate projects that launch rates to LEO should drop by factors of 2 to 4 over the next few decades. Figure 30 shows the growth of the fragment, large, and total object populations from their current distributions in 1995 shown in Fig. 28 to 2195 for a launch rate that is one quarter of the 120 launch/year peak of the last decade. The spacecraft grow at about a quarter of the historical rate of $\approx 1,240/35\text{yr} \approx 35/\text{yr}$. The fragments drop for the first three decades, and then slowly grow, regaining their initial level after about a century. The total also initially drops, regaining its initial value after about 80 years. From now to year 200, the growth is about $7,500 - 5,000 \approx 2,500$ objects, for a growth rate of about $(2,500/5,000) / 200 \text{ years} = 0.25\%/ \text{yr}$.

Figure 31 compares the present debris catalog and that predicted for year 200 for 1/4 historical launch rate. The distribution has eroded below 800 km, due to the reduced source of large objects and decay of fragments there. It has grown at higher altitudes by accumulation. The growth of the 950 km peak is modest, because the fragments have come into saturation and the source of large objects is modest. The growth at 1,450 km reflects the large launch rates to those altitudes in the historical data, which have not been adjusted to post Cold War launch patterns. The filling in of the minimum between the two peaks reflects both accumulation of direct fragment deposition and decay of fragments from above.

The principal changes in the distribution over time are the reduction at low altitudes and the growth of the higher peak relative to the lower. As these distributions are essentially linear in launch rate in this regime, the distributions for other rates can be visualized simply, e.g., for a launch rate of zero, the lower peak is largely eroded due to the rapid decay of fragments and the upper peak increases slightly due to accumulation, although that requires additional discussion below. The overall effect is a shift in importance from the lower to the upper peak—sensitive to future launch patterns.

Cascading. The previous section studied current and reduced launch rates, for which collisional cascading is a few percent effect. The Study also examined sensitivity to fragment production and cascading at launch rates larger than historical. The cascade coefficients used are derived by dividing the differential fragment production rates of Fig. 22 by the square of the catalog density at that altitude. Figure 32 shows the cascade coefficients for values of the fragment production exponent B spanning not only the values realized in experiments, but also all those that are mathematically possible. There are three distinct regions in the cascade coefficients. The coefficients are quite large at 350 km—approaching $0.001/\text{object-year}$ —due to the large objects there, which can produce many particles. However, the fragments produced there are short lived, so this peak is of limited interest. In the high collision rate, longer-lived region at 700-1,000 km, the coefficient is $\approx 10^{-6}/\text{object-year}$ for experimental values of B . Above 1,000 km, the coefficients are about a factor of three lower, so cascading there would be correspondingly slower. In the discussion below, the set of coefficients for $B = 0.7$ are taken to be the nominal values. For

parametric studies, multiples of 1x, 2x, 4x, etc. of these coefficients are used, by which is meant that sets of coefficients 1, 2, 4, etc. times nominal at every altitude are used in the calculations.

Figure 33 shows the debris predictions from two-component flux calculations for the historical launch rate, for cascade coefficients 1, 2, and 4 times the nominal values. Linear accumulation from historical launch and explosion rates and 1x (nominal) cascade coefficients produce $\approx 15,000$ catalog objects by year 100 and 25,000 by year 200. The middle curve for 2x cascade produces about the same. The top curve for 4x cascade deviates slightly by year 100 and shows a $\approx 37/25 = 50\%$ increment over linearity by year 200. Thus, for nominal launch rates, multiples of cascade coefficients even as large as those considered by NASA do not significantly enhance growth over the next few centuries.

Figure 34 shows the growth in the total number of debris objects that would result by year 200 for various launch and cascade rates relative to the 22,300 objects that would result from launch and explosions at the historical launch rate. At that launch rate, the difference between the nominal cascade rate, 1x, and no cascading, 0x, is small. Increasing to 4x would only make about a factor of 2 difference. Similarly, at 1x cascade coefficient, increasing the launch rate to 2 times the historical rate would only increase the density by about 50%, as seen in Fig. 33.

Significant cascading would only occur in the region of large multiples of the launch rate and cascade coefficient. A 3-fold increase in density is denoted by the contour that runs from 2x launch rate/2x cascade rate to 1.3x launch rate/4x cascade rate. A 3-fold increase would be about at the level of uncertainty of the current environment. The contour for a 10-fold increase goes from 2x launch rate/3x cascade rate to 1.7x launch rate/4x cascade rate. The density increase would increase sharply for larger multiples of the launch rate and cascade coefficients.

Figure 34 also shows that for lower than historical launch rates, the density falls by about a factor of ≈ 3 relative to that from historical launch for all cascade multiples, so that the debris density would only reach $\approx 22,300/3 \approx 7,400$. That is only up 50% from the current catalog, in accord with Fig. 30. For the projected 4-fold reduction in launch rate, there is essentially no growth for any cascade rate.

Figure 35 compares these Study results with the NASA prediction of debris growth for the next century⁷² cited as the "business as usual" baseline in figures presented in the National Research Council's *Orbital Debris*⁷³ and OSTP's *Interagency Report*.⁷⁴ The bottom curve is NASA's "basic population due to the continuation of the current launch activities (5% growth)." The middle curve is the Study's prediction for that launch rate and cascade coefficients 6x nominal. The top curve is NASA's prediction for base growth and cascading, presumably for 480 fragments per collision. The curves agree reasonably well throughout, and their value at the end of the century is quite close.

There are some interesting differences. The Study curve rises somewhat more steeply at the

end of the century, more closely resembling the analytic solution for cascade-dominated growth, as it should for these artificial conditions, for which cascading would be the dominant component of the roughly 10-fold growth seen. Also, the onset of the nonlinear growth phase is delayed in the Study curve relative to NASA's, which shows a sharp inflection at 20 years but then grows slowly for the next 20 years. However, the overall agreement is good, given the number of parameters that go into these calculations and the lack of detailed results for comparison.⁷⁵ It appears that for consistent inputs, Study and NASA analyses produce roughly consistent results. This agreement for conditions that most favor cascading do not necessarily indicate agreement at all other conditions, but it does imply agreement at relevant conditions.

The calculations are primarily sensitive to launch rate, fragments per explosion, and fragments per collision. The dominant factor is launch rate, because as Fig. 34 shows, at launch rates lower than historical, the calculations are insensitive to cascade rate. One aspect of launch rate requires clarification. The NASA "basic population" in Fig. 35 is said to represent "current launch activities...[at] 5% growth," which appears to be implemented by adding 5% of the current catalog, = 250 objects, to the basic population each year, which would produce roughly the 250 objects/year $\times$ 100 year = 25,000 object growth seen in Fig. 35. However, Table 1 shows that the current overall debris growth rate is about 2.7%/yr. Only rocket bodies and payloads are growing at the "historical" rate. Operational debris and fragments, which are the most numerous objects, are growing at 1%/yr, if at all. Figure 12 shows that they have hardly grown in the last two decades.

Thus, it would be appropriate to use at most the observed 2.7%/yr as the baseline for estimates, i.e., to use either the current growth rate of all debris or to use the 5% rate only for the 50% of the debris to which it applies. Either way, the consistent "historical" growth rate is about 2.7%/yr. For 2.7%/yr growth, Study calculations are insensitive to cascading for any cascade coefficient, because the debris density never reaches the levels required for the quadratically nonlinear cascade terms to become important. For "5% growth," there is little cascading at 1-4x cascade coefficient, but significant cascading at 6-8x. Thus, Study and NASA calculations would both appear to indicate that without a strong debris source from launch activities, cascading would only double debris populations in centuries or millennia. To the extent that launch rates, operational debris, and explosion rates are reduced, the onset of cascading recede even further.

These calculations mask a second discrepancy. NASA calculations are said above to use 300 fragments per explosion,⁷⁶ but even 5% "growth" actually corresponds to 0.05/yr $\times$ 5,000 obj / (120 explosions / 35 years) = 70 objects/explosion. 300 fragments per explosion would give about 5 times the as many fragments as have ever been cataloged. Thus, there should be another = 5-fold discrepancy in the fragment sources in the Study and NASA calculations, but it does not enter the comparison in Fig. 35, because in the comparison calculations, NASA specifies the source in terms of the number of fragments added per year rather than as a multiple of the launch

rate. The Study could not find NASA calculations with which to determine the impact of this additional discrepancy in calculations with variable launch rates.

The third discrepancy is NASA's use of a number of fragments per collision = 10 times larger than that inferred by the Study from DoD experimental data. With that number, for "historical" conditions, NASA predicts 10-fold growth, 60% of which is due to cascading. These NASA calculations are the principal basis for the National Research Council *Orbital Debris* and OSTP *Interagency Report*. For historical launch and explosion rates, 60 fragments per explosion, 80 fragments per collision, and standard orbital decay, Study calculations produce little debris growth and no cascading in the coming centuries. The debris increases, due to the accumulation of launch and explosion fragments, but cascading adds only a few percent.

NASA summarizes its fragment production as the product of a collision rate of 0.05 collisions/year x 480 fragments/collision = 24 fragments/year, from ~ 5,000 catalog objects,⁷⁷ which implies a rate of increase of = 24 objects/year / 5,000 objects = 0.5%/yr, or a doubling time of ~ 150 years. That is shorter than the ~ 1,000 year doubling times inferred by Study by roughly the 9-fold larger number of fragments per collision used in the NASA studies. However, cascading would not be a problem for some centuries, even for NASA's 150 year doubling time, were it not for their use of twice the current fragment source rate. Over the century, the specified external source corresponds to an effective growth of about 1.6%/yr, which raises the debris density to a level from which its cascade growth rate reaches about 1.6%/yr. Thus, the composite growth rate is about 2.7%/yr, which is an order of magnitude larger than the 0.5%/yr inferred above from collisional cascading alone.⁷⁸

These estimates were discussed in detail with NASA⁷⁹ scientists, who did not disagree with the Study's inference of a 150 year cascading doubling time from Fig. 35. They said "cascading itself is not a problem;" that they are "concerned about the possible growth due to increased launches and explosions." They said their doubling time⁸⁰ is dominated by the summation of debris from launches and explosions, and that "cascading would only become important in subsequent centuries." On these basic physical mechanisms, there appears to be agreement. The remaining discrepancies appear to be the launch rate and number of fragments per collision to be used in quantifying them further.

Overall, NASA's assumptions theoretically produce a cascade within the next century, but current launch rate projections and experimental data do not. Only assumptions that are "conservative," i.e., favorable to the production of cascading, by a factor of in launch and fragmentation rates produce strong growth in the next few centuries. NASA's calculations appear to have become "conservative" by just about that order of magnitude. However, there is no basis in experiments or theory for such conservatism. These Study results and comparisons are new; it would be useful to execute a more structured assessment of the issues and discrepancies discussed

above. Pending such an evaluation, it would appear appropriate to view AFSPC estimates as the baseline space environments and NASA's estimates as excursions from accepted models and parameters to explore conditions that might evolve if current measurements and models were in error by factors of 10 to 100.

Stability. National Research Council *Orbital Debris*⁸¹ and OSTP *Interagency Report on Orbital Debris* cite NASA analysis that indicates that the debris around the peaks at 950 and 1,450 km is strongly unstable. Those conclusions resulted from, and strongly depended on, the use of a single component model for a debris distribution with large objects only. That one-component model does not properly treat the stabilizing effect of the rapid decay of smaller fragments. The Study corrected that deficiency by developing a two-component model that follows the evolution of both large objects and fragments.⁸² While more complex, the two-component model can be solved analytically to determine its steady state solutions by extensions of the techniques used for the one-component model. Figure 35 shows the critical densities, i.e., the debris density at each altitude above which the rate of production by collisional cascading would exceed the rate of decay, for the one- and two-component models. The top curve is for the two-component model, for which the critical density ranges from 9,000 objects in the 100 km bin at 850 km to about 300 at 1,550 km. The curve identified by solid squares is the curve for the one-component model, which falls from about 2,000 to 100 objects. The curve identified by open squares is the current catalog of Fig. 1.

The curve for the two-component model lies above the catalog at all altitudes, which indicates that, in the absence of other sources, the two-component catalog is stable at all altitudes. The margin of stability is very large, $\approx 3,500 - 1,000 \approx 2,500$ objects at 950 km, but only ≈ 100 objects at 1,450 km. The curve for the one-component model falls slightly below the catalog at 950 km and ≈ 600 objects below the catalog at 1,450 km. Each of those crossing represents potential instability; the former slight and the latter serious. This one-component curve and these inferences lie very close to those of the earlier NASA analysis,⁸³ which is appropriate, in that for these assumptions, it should and does reduce to that analysis.

However, the top curve shows that when both components are treated properly, in the absence of external sources, the catalog is stable at all altitudes—by a large margin low altitudes and a narrower margin at higher altitudes. The reason for the difference between the one- and two-component curves is primarily orbital decay. The removal of objects by decay stabilizes growth. In the NASA one-component model, all objects are treated as large, intact objects, which have a decay times at 950 km of ≈ 1000 years. Thus, they don't decay on relevant time scales; are not stabilized; and will grow rapidly after some point in time.

In the two-component model, the fragments, which are about 70% of the objects produced by collisions, have an areal density about a factor of 30 lower, so they have decay times of ≈ 30 years. Thus, they do decay on relevant time scales, and are stabilized. Moreover, this reduction in

the growth and number of fragments reduces the fragment flux, so the rate of collisions with large objects is reduced, which further reduces the rate of production of new fragments. The net effect is the difference between the two curves on Fig. 36. There is no question that a two-component model is a better approximation to the actual debris distribution than a one-component model; the one-component curve on Fig. 36 is only an approximation to the two-component curve. As its predictions are generally off by about an order of magnitude—i.e., by about the ratio of the large object and fragment areal densities—and gives the wrong assessment of stability, the one-component model would not appear to be a useful approximation for this assessment.

The comparison above was performed in the absence of external sources, the case used in NASA analyses. However, external sources from launch, deployment, and explosions exist and are dominant above about 900 km. There, they can cause secular growth, which must be stopped before it reaches levels where cascading is self sustaining.⁸⁴ Figure 37 shows the current, critical, and projected sources in the altitude regime of concern. The top curve is the current source, which is large. The curve indicated by open squares is the critical source, i.e., the source above which the two-component flux becomes unstable. The curve indicated by solid diamonds is the source for projected launch rates, which is about a factor of 10 below the current source. The current source lies above the critical source at all altitudes, which means that the current debris distribution is growing at all altitudes. The difference between the current and critical sources is smallest at 850 km, where it is about 20/year. The gap is an order of magnitude at 950-1,250 km. It grows to a factor of 100 at 1,450 km. Decreasing the sources to projected levels would restore stability at altitudes up to 1,300 km, but would still leave an order of magnitude gap at higher altitudes.

The time scales for action are different at different altitudes. From Fig. 36, at 950 km, the stability margin is about 2,500 and from Fig. 6, the source there is about 6 large objects per year, so the peak at 950 km requires action within a few hundred years. Decreasing sources by the projected order of magnitude by then should retain strong stability there. At 1,450 km the margin is ≈ 100 objects and the growth is ≈ 3 objects/year, so action could be required there in a few decades, if the CIS continues to launch to that altitude. NASA's one-component model calls for immediate de- or re-orbit of all large objects at all altitudes, based on overly simplistic analysis. The Study results indicate that the low altitudes can wait but that high altitude sources should receive prompt attention. Those regions would not be unstable now in the absence of large sources. Because fragments and large objects are both important in the two-component models, both launch and fragment reduction should be effective mitigation measures.

The response time estimates of the previous paragraph are conservative, because they assume that all of the fragments produced by collisions remain in the 100 km bin in which they are born, where they cause further collisions. As noted above, many fragments will be distributed over a much larger range in altitudes. Figure 2 shows that the spacecraft peak at 1,450 km is less than

100 km wide and that the debris peak is only slightly wider. Particle deposition is over wider regions, as shown in Fig. 26. Thus, a spread of over 100 km greatly reduces the local fragment source. NASA estimates that about a third of the fragments are deposited in a 100 km bin, based on the confined velocity model of Fig. 19.⁸⁵ The larger velocities and wider variances of Figs. 16, 18, and DoD railgun data would give a wider spread and lower local deposition.

Figure 38 shows the predicted growth in fragments and large objects for the current launch related sources for each, using NASA's assumption of 1/3 local deposition of collisional fragments. The growth of both components is secular until about year 500, after which they grow more rapidly due to cascading. At that point the debris has reached about 10,000 objects, which is about 15-fold growth from its current level. That level would not represent a direct problem. The calculations above indicate it would give a collision rate of $\approx 6 \times 10^{-2}/\text{yr}$ on a 40 m^2 satellite. The threat to rockets transiting the altitude on their way to deep space would be trivial. However, the debris increases another factor of 3 in the next 500 years, and could 10-fold again before the source material was exhausted. Thus, it would be useful to prevent this growth, both to maintain the usefulness of this altitude region and to minimize the amount of material ejected to other more prominent orbits. That could be done by reducing the source rate or reducing the fraction of material deposited locally. The fraction of material deposited locally cannot be controlled, but it should be understood. The source rate could be reduced in proportion to the launch rate of material to this altitude.

Figures 36 and 37 assumed that all fragments were deposited locally. Fig. 38 used NASA's assumption that 1/3 was deposited locally. The actual fraction is as uncertain as the debris velocities discussed above. Thus, Fig. 39 varies the local deposition from 10 to 60% and the source rate from 10 to 90% of historical levels. For 10% source rates, the increase over the millennium is about a factor of 3, independent of the deposition fraction. At the current source rate, about 50% of peak, there is about a factor of 3 variation as the local deposition fraction varies from 10 to 60%. At 90% of the historic peak, there is about a factor of 10 variation. Overall, the sensitivity to the deposition fraction is small at small source rates, because there are few cascade fragments to distribute. The sensitivity is large at historic rates, but such rates are no longer projected. At current and smaller rates the sensitivity is modest. In that region, the growth over the millennium for nominal 30% source and deposition is about a factor of 10, which is about a factor of 5. Thus, it appears that projected rates may reduce growth rates to a point where cascading would be delayed for thousands of years. Slightly greater reductions in launch rate to this altitude would essentially eliminate it altogether.

Geosynchronous altitude fragments are spread over volumes several orders of magnitude larger than those at LEO; thus, impact and growth rates are reduced accordingly. Moreover, relative velocities are reduced by an order of magnitude, which makes fragmentation

requirements about a factor of 100 more demanding. Figure 40 from *Orbital Debris* shows that 20 explosions would produce less of a debris hazard than the normal meteoroid background at GEO.⁸⁶ An early Aerospace assessment appeared to be at variance with this result, but on inspection, actually produced similar conclusions.⁸⁷ Thus, the debris problem at GEO should remain small for the foreseeable future. As noted above, DoD, civil, and commercial launches are shifting to GEO for operational advantages, which should provides a clean environment for important payloads there for centuries as well as reducing the sources at LEO, which is being left to commercial activities that are capable of policing themselves.⁸⁸ After this independent evaluation, the Study concurred with NASA and Aerospace's assessment that the impact problem at GSO is minimal for the foreseeable future.

Launches to GEO involve geosynchronous transfer orbit (GTO) boosters, which revisit GEO daily for the few decades until they decay. They, and objects associated with them, spend little time in LEO or GEO; they spend most of their time in transit. Their effect on LEO is included in the calculations above. However, explosions in certain phases of their orbits could produce some fragments that could intersect occupied GEO orbits, so it is appropriate to use the same burn-to-completion and debris minimization measures for them as well.

Comparison. During the Study, there were fruitful interactions with a number of parallel efforts, most notably the National Research Council, OSTP, and NASA. As the Study was starting, the National Research Council completed and published its study of *Orbital Debris*, which was a valuable source of information. The Study had an opportunity to meet with the Chairman of the National Research Council study and explore the main differences in approach and assessment, which were *Orbital Debris'* reliance on the Haystack data despite the ambiguities discussed above, its acceptance of NASA growth predictions based on high launch and fragmentation rates, its acceptance of a one-component model for the discussion of stability, and recommendation for prompt deorbiting of spacecraft and rockets, which appears premature given these uncertainties.

The Study also had the opportunity to interact indirectly with the OSTP Interagency Study, which was a useful source of information on the current environment, measures, and policies. The issues addressed above are its use of the Haystack data, its use of EVOLVE predictions based on high launch and fragmentation rates as the basis for environment predictions, and its use of DoD calculations that are undocumented and apparently incorrect, or at least inconsistent with the parallel NASA calculations, as the basis for long-term predictions.⁸⁹

The Study had four useful interactions with NASA efforts, first to learn about their efforts, second to discuss their models and experiments, third to question details of fragmentation and cascade calculations, and fourth to interact in detail on technical issues ranging from launch rate through environments to stability. Those discussions are documented in a series of reports,^{90,91} which explored preliminary versions of the technical arguments above.⁹² Most of those points

have been addressed in the sections above. However, in a letter to the Air Force Secretariat, NASA Headquarters reiterated four points that clearly bear reemphasis: mass on orbit, Haystack data, fragmentation, and launch rate.⁹³ Briefly:

1. Mass in orbit. As noted above, there is no significant disagreement on this quantity; none at all on collision rate, which is the more significant related quantity. This comment may stem from an earlier analytic treatment that gave a factor of two disagreement because it used NASA's earlier areal density of 60 kg/m^2 for all objects.⁹⁴ Corrected by a factor of $150/60 = 2.5$ for the overall 150 kg/m^2 estimated above for all objects, the analytic model also agrees on mass and collision rate. The AFSPC catalog does not track mass; it tracks area, the quantity actually used for collision and fragmentation rates, on which Fig. 1 indicates AFSPC and NASA agree.

2. Can NASA "infer size distribution from Haystack?" NASA's letter concedes the Study's main point in stating that "NASA and the SAB agree that no inference of size can be made from the radar return of a single object passing through the beam." The Study further shows that no practical amount of observation time in the current mode will make it possible to compensate for that "insufficient statistical data." The NASA letter shifts to a more modest goals of "objects between 1 and 10 cm." At the fourth meeting, NASA claimed high confidence at 1 mm, which is needed for its current shielding approach, and useful statistics for even smaller particles. As noted in the notes for those meetings,⁹⁵ Haystack variances are an order of magnitude larger than their mean at 10 cm and could not be reduced to useful levels by any practical amount of observation with Haystack.

The issue raised by the Study is broader than Haystack. It is that the environment at Space Station altitudes is apparently not known with any confidence, and that current experiments will not determine it. Thus, it is not known whether the currently prescribed shielding is necessary, let alone adequate. That is reflected in the fact that the Haystack data and models have been reduced by an order of magnitude in the last year, but the requirements have not.

3. The NASA letter states that "NASA calculates a larger number of fragments from a given collision than the SAB." This point was addressed at each of the meetings with NASA. It is shown above that the Study's fragmentation model agrees with laboratory, field, and on orbit data and current analysis. In the last meeting with NASA it was shown that the Study and NASA models also involve the same average mass per collision.⁹⁶ Figure 24 shows that the DoD model that reproduces the number of fragments observed in the Atlas explosion and DNA tests cannot produce the 5 to 10-fold larger number used in NASA analyses. This discrepancy has been discussed several times; NASA's response is that its assumption is conservative. The only basis for NASA's number is the statement that "an average collision produced 1600 kg of fragments...so that an average collision would produce about 480 fragments larger than 10 cm."⁹⁷ No basis is given for either number, and the two taken together are inconsistent with the scaling from the Atlas

and DNA experiments. Thus, rather than say that NASA *calculates* a larger number of fragments, it would be more correct to say that NASA *uses* a larger number .

4. NASA states it has "no preferred traffic model...this is an area that requires further analysis...[NASA] is prepared to input any SAB model," which is a useful response. To date, NASA has studied growth rates at historical and larger launch rates, which are primarily useful as excursions to study the effect of the return to high launch rates. It would be useful for NASA to do predictions for the projected launch rates that fall by factors of 2, 4, and 8 over the next two decades for comparison with the results above for current projections.

In the discussions with NASA, there was an additional set of connected technical issues in the areas of impactor area, fragmenting collisions as a function of impactor size, and the overall importance of large objects compared to fragments. Since the last meeting, there has been significant progress on each. While it is difficult to evaluate the effect of impactor area for general distributions, Fig. 2 shows that in the catalog region, the flux scales as $\approx 1/\sqrt{A}$. For a power law the fragmentation rate can be evaluated analytically, either treating or ignoring the impactor area relative to the target area. The ratio of the two calculations is about 1.4, relatively insensitive to the details of flux distribution and independent of fragment mass-area scaling. The analytic model apparently overestimates the error, but even 40% would be less than the error associated with interpreting UHF cross sections as geometric cross sections, let alone interpreting their quadrature sum as a collision cross sections in NASA calculations. Moreover, the impactor area correction is similar for collision and fragmentation rates, so in taking their ratio, it cancels out, and has little impact on the number of fragments per collision.⁹⁸

The second issue was the fraction of collisions that are catastrophic , i.e., those that produce large numbers of fragments, that involve small impactors, which NASA held to be small in the fourth technical discussion. It is also possible to evaluate that fraction analytically.⁹⁹ Figure 41 shows the percentage of catastrophic collisions that involve collisions between large objects with large objects (L-L), medium sized objects with medium sized objects (M-M), and medium objects with large objects (M-L) as a function of the "boundary" mass or area defining the distinction between the M and L objects. Sub-catalog objects smaller than 1 kg are ignored. For small boundary masses, almost all objects are by definition L objects, so most collisions are L-L collisions. For large boundary masses, there are few L objects left, so most collisions are M-M. The region from 30 to 300 kg is transitional. Up to 30 kg, L-L collisions dominate. Then M-L collisions take over. By 300 kg the L-L collisions fall below M-M.

The definition of the boundary mass is arbitrary, but the qualitative results are relatively insensitive to the choice in this transitional region. At 10 kg the L-L collision rate is about twice M-M; at 100 kg the M-L collision rate is about twice L-L. But throughout the region, the two are comparable and about an order of magnitude larger than M-M collisions—which again represents

the fact that it is the flux of the numerous smaller fragments on the area of the fewer, large objects that contributes the bulk of the collisions.

NASA uses a boundary mass definitions of 100 kg, for which it predicts that about 40% of the collisions are M-L and the rest are L-L.^{100,101} This ratio is slightly lower than that shown on Fig. 40 for 100 kg, but not too dissimilar to the ratio that would result from a definition of about 30-40 kg. Both calculations involve essentially arbitrary definitions of boundary mass, but both predict that for reasonable values, M-L and L-L collisions are comparable and an order of magnitude larger than M-M. Thus, there would not appear to be any significant disagreement on the fact that both fragments and large objects are important to fragment production, although the point has been raised repeatedly.

The third point is the overall importance of large objects compared to fragments. In the technical meetings, NASA scientists repeatedly argued that "small objects do not matter;" it is only the large, intact objects that matter for debris production and growth. Those statements are obviously inconsistent with the results demonstrated and discussed in the previous paragraph—including those published by the principal NASA scientists in this area. The paragraphs above have shown that the area of small fragments matters little, but because of their large numbers, their contribution to the fragmentation rate is significant—even dominant. A by product of those calculations is the prediction that if the collisions involving impactors smaller than 100 kg was ignored, the total catastrophic collision rate would be reduced by a factor of 2 to 3. It is plausible to look at the fragments in Fig. 12, which are saturating, and the total mass in Fig. 21, which is not, and conclude that only the large objects matter. But much of the mass is at altitudes too low to matter. And even at altitudes where the fragments from the large objects do survive for significant times, it is the product of the flux fragment and large object densities that matters, which must be kept in mind when mitigation strategies are considered.

In summary, on the issues raised by NASA, there is no disagreement on mass on orbit, on which the catalog is silent and the studies are about equally ignorant. NASA conceded the Study's main point about Haystack, that its data is ambiguous. NASA agrees that it assumes a factor of 5-10 more fragments for a given collision mass, and states that its launch models are only for exercise. On the seemingly controversial issues of small fragments versus large, there is actually no significant disagreement in the calculations, only in definitions. The results are clear: they are about equally important. It would appear that the only remaining technical issue is the justification of NASA's launch and fragmentation rates, either one of which could reverse their conclusions about growth. Their conclusions about stability simply result from an overly simplified model. These conclusions were put to NASA, which agreed to provide us with a list of those to whom they had sent their and our draft materials. That has not been provided, so the interaction is in abeyance, which does not represent any particular impediment to the conclusion of the Study.

Summary and conclusions. The Study addressed and resolved a number of issues in space debris launch, explosion, collision, fragmentation, and decay physics—solving some and bounding the rest. It showed that the AFSPC and NASA catalogs are consistent, apart from completeness and extrapolation to centimeter sized objects, which does not impact AFSPC's DoD responsibilities. The Study helped bring NASA's measured and model environments at 400-500 km into closer accord, advanced the interpretation of ambiguous radar data on small objects, and showed that impacts at 900-1,000 km would reduce satellite lifetimes slightly, not cascade.

The Study made an important first step in interpreting the impact of recent reductions in launch rates and in projecting the impact of current trends and policies on future launch and explosion rates. Launch rates in LEO will fall sharply due to reduced CIS launches and the shift of defense and commercial payloads to GEO. This shift should have a major stabilizing effect on debris growth in LEO; indeed, it could stabilize debris growth all by itself, as it is the dominant input. The Study brought that fact to the attention of other agencies, which were unaware of these trends and were using peak historical rates, which distorted their results.

The benefits of the current debris policy have been questionable and have saturated—along with the fragments that are the dominant component of the debris today. The rate of explosions, and the fragments per explosion, have stabilized. There is some capability to interpret and predict how they might involve in the future. The rate of collisions is understood theoretically, although there is no really relevant data. The fragmentation rate is controversial. Although there are useful data from laboratory, field, and space experiments, on which the Study normalized its analysis, NASA assumes other values, in perhaps the most obvious disagreement in the current analysis. The Study found important differences in treatments of orbital decay that impact discussions of long term stability.

For similar assumptions, Study and NASA models yield similar results; however, there are significant disagreements about assumptions—despite the extensive theoretical and experimental basis for those used by the Study. The key issues are the amount of conservatism in NASA analyses of launch, explosion, fragmentation, and decay rates. For nominal rates, Study models produce little debris growth and no cascading for conditions where JSC models predict 10-fold growth due to cascading. In that comparison, the difference could be traced to the number of fragments per collision. Until these issues are resolved, it is appropriate to view the AFSPC estimates as the baseline and NASA's estimates as very large rate excursions. For projected launch rates, these sensitivities are largely eliminated, and stability should be predicted by all analyses.

NASA's launch rate is high by perhaps a factor of 4. NASA's estimate of the number of fragments per explosion is high by about a factor of 5 relative to historical data, NASA's estimate of the number of fragments per collision exceeds that from detailed measurements and estimates by a factor of 5-10. These factors are multiplicative; thus, their overall impact is an increase by a factor

of 100 in NASA's estimates those factors that favor a cascade relative to the factors used in standard analyses. If any of NASA's parameters are replaced by the nominal values, cascading is delayed for centuries. Of these assumptions, the most significant for the discussion below is NASA's use of a number of particles per collision six times higher than that inferred from detailed analyses. While NASA has stated that this higher number is used for "conservatism," there is no basis for an order of magnitude of conservatism in the data or analysis.

NASA analyses indicate the debris around 950 and 1,450 km is strongly unstable. The Study showed those conclusions resulted from an over simplified model, corrected it, and showed that in the absence of external sources, the catalog is currently stable at all altitudes. External sources from launch, deployment, and explosions are dominant above about 900 km. They cause secular growth that must be reduced before cascading could reach self-sustaining levels. The low altitudes should be addressed within a few millennia; the high altitudes could require more prompt attention. GEO fragments are spread over very large volumes, which greatly reduces collision and growth rates. Thus, the debris problem at GSO be modest for the foreseeable future.

Recommendations. Space debris has not been shown to be an issue in coming centuries; thus, it does not appear necessary for the Air Force to take additional steps to mitigate it. It would be appropriate for the AFSPC to monitor launch, explosion, and fragmentation rates as well as the composition and evolution of the catalog as part of its responsibility as the DoD agent for space. It would be appropriate for AFSPC to be involved in inter agency and international analysis efforts, to broaden its inputs and outputs, and to publish scientific papers assessing the expected space debris environment on the basis of their measurements, empirical parameters, and models.

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Fig. 1. Number densities versus altitude from AF and JSC catalogues.

particles vs z; A

Fig. 2. Object number versus altitude and area from catalog.

Fig. 3. **Approximate Debris Flux in LEO**

Fig. 4. Evolve Environment / SSN Catalog (Jan 1990)

Fig. 5.

Orbital Debris Flux

Haystack 90° Staring Data - 1990-1994; 450-500 km

Fig. 6. Scattering cross section for a metal sphere.

ORBITAL DEBRIS FLUX

HAYSTACK STARING DATA - 1990-1993 - 850-950 km

Fig. 7. Measured and modeled orbital debris flux for Haystack 90° staring angle data for the altitude range of 850 - 950 km.

Figure 8 **Total Launches Compared to Total Launches to LEO**

Fig. 9.

PERCENT OF PAYLOADS LAUNCHED INTO LOW EARTH AND DEEP SPACE ORBIT VS TIME

10 rate for 100/4 & 1000/2 vs t

Fig. 10. Total global launches to LEO per year for various LEO communication constellations.

frag/bin vs z; # frag

Fig. 11. Fragment distribution as a function of fragmentation altitude and number of fragments per explosion.

Figure 12. On-orbit cataloged population (corrected for delayed cataloging).

Source: Orbital Debris (National Research Council)

Figure 13.

Total Objects in LEO Compared to Objects with Perigee < 800 km and > 800 km

Fig. 14. Atlas Cumulative Number/Mass Distribution.

Fig. 15. Atlas Fragment Size

Ballistic Coefficient Distribution Landsat 3 Explosion

Fig. 17. Log of Area per Mass

Fig. 18. Landsat 3 R/B debris cloud of 90 identified fragments four days after the event as reconstructed from U.S. Space Surveillance Center database.

Fig. 19. Debris Velocity Distribution

NASA Johnson Space Center
Houston, Texas

Lockheed

Fig. 20. Differential and integral collision rates versus altitude.

AD0004

Fig. 21.

dQ & Q vs z

Fig. 22. Differential and integral fragment production rate versus altitude.

Fig. 23. Cumulative distribution and debris size versus fragment mass from SOCIT 3.

cat & num frag/coll vs B

Fig. 24. Fragments per collision from catalog and numerical estimates versus production exponent.

Fig. 25. Catalogued and remaining fragments versus altitude.

Fig. 26. Composition of remaining density as a function of altitude.

fractional error in limit flux

Fig. 27. Ratio of actual density to NASA *equilibrium spatial

Comp cat vs z

Fig.28. Components of catalog versus altitude.

N frag, large, & tot vs t; proj

Fig. 29. Fragment, large, and total number versus time.

comp of N vs t; 1/4 rate

Fig. 30. Fragment, large object, and total density versus time for 1/4 historical peak launch rates.

N tot vs z; 0 & 200 yr

Fig. 31. Total object distribution at present and in 200 years for 1/4 current launch rate.

cascade coeft vs z; B

Fig. 32. Cascade coefficient versus altitude for various values of fragment production coefficient B.

N vs t; alp

Fig. 33. Debris density versus time for historical launch rates and various cascade coefficients.

N vs x launch; x alp, 200 yr

Fig. 34. Growth of total number of debris particles through year 200 versus multiples of launch rate and cascade α

N, JSC N, JSC base vs t

Fig. 35 Study and NASA predicted densities for twice the historical launch rate and 6 times the nominal cascade rate.

1 & 2 crit densities & cat vs z

Fig. 36. One and two component critical densities and catalog versus altitude.

sources vs altitude

Fig. 37. Current, projected, and critical sources versus altitude.

n frag & lg vs t; 1,450 km

Fig. 38. Predicted debris densities at 1450 km for current launch rate.

growth vs % local dep; rel sou

Fig. 39. Debris growth at 1,450 km versus fractional source & deposition.

Fig. 40. Probable Orbital Debris Environment in GEO Resulting from 20 Satellite Breakups

% catastr coll by type vs bound

Fig. 41.

Percentage of catastrophic collisions by impactor and target type.