AN UPDATE OF THE TOP 50 LIST

Darren McKnight[(1)], Erin Dale[(2)], Joe Cassady[(3)], Andy Ratcliffe[(4)], Satomi Kawamoto[(5)], Alessandro Rossi[(6)], and Dmitriy Grishko[(7)]

(1) *LeoLabs*, 4795 Meadow Wood Ln, Chantilly, VA 20151, *USA*, darren@leolabs.space
(2) *LeoLabs*, 4795 Meadow Wood Ln, Chantilly, VA 20151, *USA*, *edale@leolabs.space*
(3) *L3 Harris, 2610 Lemontree Lane, Vienna, VA 22181, USA, joe.cassady@l3harris.com*
(4) *UK Space Agency, Harzwell Campus, Oxforshire, UK, andrew.ratcliffe@ukspaceagency.gov.uk*
(5) *Japan Aerospace Exploration Agency, 7-44-1 Jindaiji-Higashi-machi, Chofu, Tokyo 182-8522, Japan, kawamoto.satomi@jaxa.jp*
(6) *IFAC-CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy, A.Rossi@ifac.cnr.it*
(7) *Bauman Moscow State Technical University, 2-nd Baumanskaya, 5, 105005, Moscow, Russia, dim.gr@mail.ru*

ABSTRACT

The accumulation of intact derelict objects in low Earth orbit (LEO) has been a subject of analysis for decades. Around the turn of the century the realization of the debris-generating potential of this growing population motivated the global community to establish the 25-yr post mission disposal rule. To provide an operational focus a number of organizations started assembling long lists of number, mass, and nationality of this abandoned hardware. In 2020, a team of 19 experts from 13 countries assembled to create a definitive list of objects that would most directly minimize the long-term debris-generating potential in LEO and potentially serve as a "priority list" for active debris removal (ADR) operations.

The number and mass of derelict objects has continued to grow, motivating the need to update this list. In addition, there are now many more operational satellites than in 2020, largely linked to the deployment of the Starlink and Eutelsat OneWeb constellations. There has also been increasing research into the sustainability of the space environment which has identified certain regions in LEO with an elevated probability of collision (PC) that should be considered when evaluating the most important objects to remove. Alongside these developments, LeoLabs has developed a suite of analytic tools that can be used to automate many of the algorithms used in the original "Top 50 paper."

A new list of the top 50 objects suggested for removal from LEO has been developed considering (a) aggregate collision risk (i.e., PC multiplied by consequence) since 1 January 2022, (b) orbital persistence of fragments (if a collision occurs), and (c) proximity to existing altitudes where aggregate risk of the population is the largest (e.g., altitude bins centered around 775 km, 840 km, 1000 km, and 1450 km).

The benefit of the current method is to apply a team approach to adjusting filters to a single model, however, the implication is not that this model is the only way to select the top 50 objects. A comparison between the 2020 "Top 50" list and the newly generated list is provided to iilustrate key lessons for debris hazard evolution and to potentially inform future ADR missions. The current list does not commit the organizations involved to pursuing the removal of the objects identified but instead provides continued insight to the international community on where the greatest gains to the environment could be gained by future operational ADR missions.

1. INTRODUCTION

The accumulation of orbital debris in low Earth orbit (LEO) has received increasing attention as:

- fragmentation events continue to occur: there have been typically four to six breakup events in LEO annually since the turn of the century [1];
- over the last 20 years, long-lived rocket body mass is accumulating at rates faster than during the dawn of the space age [2]; and
- the number of LEO operational satellites is growing exponentially: from only 1,000 in 2015 to over 10,000 in 2025 with ~28,000 expected by 2029 and potentially ~100,000 by 2039 [3].

As early as 2009, NASA identified 500 objects to be considered for removal to help control the growth of fragments from explosions and collisions of intact derelict objects [4]. Years later, this large list was reduced by international research teams examining both the probability and consequence of potential collision events (i.e., risk) to identify the top 50 objects in LEO that should be considered first for targets of active debris removal (ADR) [5-7].

The purpose of this paper is to update the top 50 list due to the continual abandonment of intact derelicts (i.e., rocket bodies and non-operational payloads). The continued growth in the number of massive derelicts in LEO requires we actively refine the identification of the objects to be removed and try to break down the barriers to ADR becoming an operational mission solution [8].

2. TECHNICAL APPROACH

The figure below details the approach to determine the list of the top 50 objects recommended for removal from low Earth orbit (LEO).

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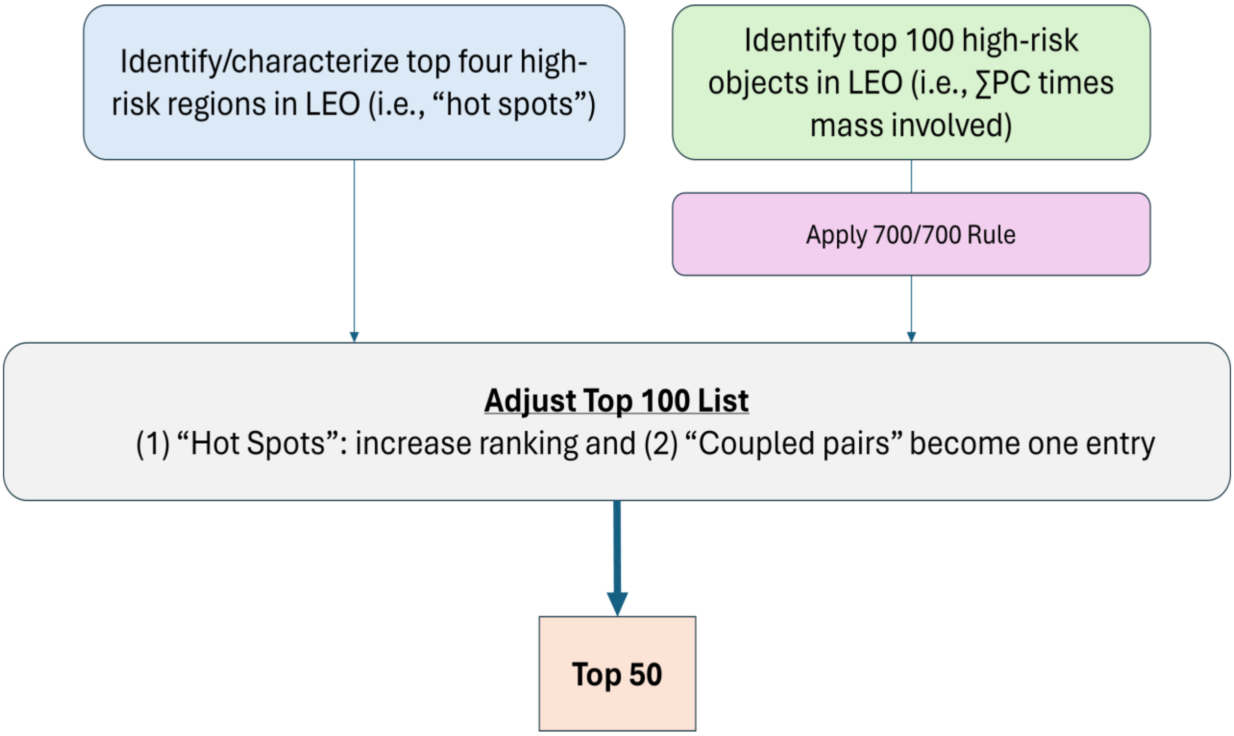

Fig. 1. The top 50 objects in LEO will be identified by considering both risk features for the individual objects and risk features for regions in LEO where collision risk is the highest (i.e., "hot spots").

Originally, there were three major steps in this process (Fig. 1).

- Identify top 100 Objects. Using the LeoLabs LeoMap tool, the empirical cumulative risk from all conjunctions logged from 1 January 2022 to 31 December 2024 with a probability of collision (PC) greater than 1E-6 is used to produce the initial list of objects. The order is based on the cumulative risk (i.e., PC multiplied by mass involved for all conjunctions) for each object. The PC criterion of 1E-6 is chosen because that threshold covers all relevant operational events.
- Identify and Characterize "Hot Spots". There are four regions in LEO where the accumulation of massive, long-lived derelict objects creates regions with the greatest risk for collisional fragmentation events. The assertion here is these "hot spots" are regions where events will be the most likely and consequential, thus are relevant to the final selection process for the top 50 objects.
- Adjust Top 100 List. The team investigated two ways to modify the top 100 list.
    a. "Hot Spots". The order of objects from the initial top 100 list can be adjusted based on a weighting by inclusion in the hot spots since a high-risk object in a high-risk region is seen as more important to remove than a high-risk object in a lower risk region. **The reader should be cautioned that the top 50 list is not a prediction of the order in which collisions are predicted to occur but rather a statistical evaluation of objects that, if removed, would reduce the debris-generating potential in LEO.** It has been stated by one of the authors on numerous occasions, "the most likely event is likely not the next event to occur."
    b. "Coupling": During the compilation of the original top 100 list, pairs of objects whose cumulative risk depends on each other by a significant amount of their cumulative risk will be considered "coupled". This means they will share a slot in the top 100 list, implying as soon as one of the two is removed, the other one will drop in priority as part of the top 100 (or 50) object list.

2.1 Identify Top 100 High-Risk Objects

LeoLabs' LeoMap tool created the top 100 objects purely based on cumulative risk; this original top 100 list is included in Appendix A. That list was then filtered by excluding (1) all objects with a mass less than 700 kg (which includes all fragments), and (2) all objects residing below 700 km altitude. This process is called the 700/700 Rule. These objects are omitted as they are not good candidates for ADR because they are either too small to be worth removing or too low in altitude and would decay within a few decades on their own. Tab. 1 depicts the new interim top 50 list having applied the 700/700 Rule.

Table 1. The Interim Top 50 list using the 700/700 Rule looks like the 2020 Top 50 List with rocket bodies contributing greatly but the SL-16 R/Bs are not all clumped in the first 20 slots.

#	Object Name/SATNO	Risk, kg	Count	Mass, kg	Ave Alt, km	Incl, deg	Launch
1	28353 (SL-16 R/B)	283	341	9000	844	71.0	2004
2	27386 (ENVISAT)	175	276	8211	762	98.3	2002
3	7727 (COSMOS 724)	135	25	3769	897	65.6	1975
4	19120 (SL-16 R/B)	117	366	9000	827	71.0	1988
5	24279 (H-2 R/B)	115	133	2700	1082	98.7	1996
6	39203 (CZ-2C R/B)	107	142	4000	705	98.4	2013
7	22565 (COSMOS 2237)	106	64	3200	851	70.8	1993
8	5917 (METEOR 1-11)	94	33	1200	862	81.2	1972
9	16292 (SL-8 R/B)	86	33	1435	974	82.9	1985
10	28060 (SERVIS 1)	86	11	840	992	99.5	2003
11	19650 (SL-16 R/B)	71	262	9000	839	71.0	1988
12	15986 (COSMOS 1677)	60	19	3769	940	64.7	1985
13	36123 (CZ-4C R/B)	60	37	2000	1086	100.5	2009
14	22823 (SPOT 3)	59	67	1869	826	98.9	1993
15	24304 (COSMOS 2334)	59	16	820	986	82.9	1996
16	44548 (CZ-2D R/B)	55	225	4000	757	98.3	2019
17	16511 (SL-8 R/B)	52	51	1435	978	82.9	1986
18	25590 (COSMOS 2361)	51	12	820	988	82.9	1998
19	11511 (SL-8 R/B)	50	89	1435	765	74.0	1979
20	20625 (SL-16 R/B)	48	344	9000	843	71.0	1990
21	23603 (COSMOS 2315)	47	14	820	989	82.9	1995
22	25407 (SL-16 R/B)	46	323	9000	839	71.0	1998
23	24298 (SL-16 R/B)	44	280	9000	851	70.8	1996
24	6019 (COSMOS 489)	43	13	820	978	74.0	1972
25	8344 (SL-8 R/B)	43	117	1435	758	74.1	1975
26	25567 (NADEZHDA 5)	43	17	825	992	82.9	1998
27	25400 (SL-16 R/B)	40	331	9000	805	98.8	1998
28	17590 (SL-16 R/B)	40	348	9000	835	71.0	1987
29	16012 (SL-8 R/B)	40	83	1435	767	74.1	1985
30	39261 (CZ-4C R/B)	33	168	2000	779	98.9	2013
31	23774 (SL-8 R/B)	33	63	1435	975	83.0	1996
32	22566 (SL-16 R/B)	30	293	9000	842	71.0	1993
33	22220 (SL-16 R/B)	30	330	9000	836	71.0	1992
34	24773 (SL-8 R/B)	29	45	1435	986	82.9	1997
35	16182 (SL-16 R/B)	28	359	9000	837	71.0	1985
36	23705 (SL-16 R/B)	28	331	9000	841	71.0	1995
37	23405 (SL-16 R/B)	27	364	9000	841	71.0	1994
38	10531 (COSMOS 970)	27	13	2000	1036	65.9	1977
39	22803 (SL-16 R/B)	26	341	9000	835	71.0	1993
40	57831 (CZ-6A R/B)	25	12	5800	801	86.0	2023
41	39014 (CZ-4C R/B)	25	71	2000	995	63.4	2012
42	28480 (CZ-2C R/B)	25	135	4000	803	98.2	2004
43	41858 (CZ-2D R/B)	24	242	4000	769	98.6	2016
44	17974 (SL-16 R/B)	22	354	9000	834	71.0	1987
45	26070 (SL-16 R/B)	22	298	9000	840	71.0	2000
46	22285 (SL-16 R/B)	22	341	9000	841	71.0	1992
47	21088 (SL-8 R/B)	21	42	1435	973	82.9	1991
48	13114 (SL-14 R/B)	20	36	1407	947	82.5	1982
49	12319 (COSMOS 1249)	20	27	3769	940	65.0	1981
50	4589 (SL-8 R/B)	19	95	1435	749	74.1	1970

2.2 Identify and Characterize Four "Hot Spots"

Tab. 2 provides key features of the four "hot spots" in LEO. The name of the cluster is delineated by the centering altitude (e.g., for C840 the spatial density of massive derelicts is the highest at 840 km). Next, the altitude span of the clusters is provided. Objects reenter fairly quickly below 700 km so they would likely not be good candidates and there are not enough derelict objects or operational satellites above 1,600 km to be considered part of a "cluster". The number of objects and the average mass of these objects provide an understanding of the size of the challenge within each of these clusters. The three features the clusters are rated on total risk, "PC by" 2025, and persistence [9].

The total risk of all objects in each of the clusters is summed up in the next column. Note using this debris-generating potential term again (i.e., the individual values used to build the initial top 100 list) the model may overweight this term. The authors propose this weighting is appropriate as the use of the eventual top 50 list is provided to examine where LEO needs to be remediated as much as exactly which objects should be removed. *Further, the top 50 list is not provided to predict exactly which objects are most likely to be involved in collisions. Rather, the list provides an examination of objects and the regions where these objects might collide.* There are also other issues, as will be discussed later in this paper, that may drive the exact order and priority for removal of these objects. The authors feel it is critical to be clear on this process as it serves to prevent misinterpretation of the results.

Probability of collision (PC) by 2025 is calculated as per the development in Appendix B as first applied in [9]. The "PC by" 2025 is a cumulative Poisson probability for a collision rate between the massive derelicts in each cluster since the median year the massive objects in these clusters were abandoned. The mean year of abandonment is roughly 1984, resulting in a 40-year risk calculation to yield "PC by" 2025.

The persistence score is based on the orbital lifetime of an intact object (i.e., area-to-mass ratio of 0.01 m^2/kg) at the "center" of the cluster. Orbital lifetimes are calculated using the classic development from King-Hele [10]. The orbital lifetime values in years for the four clusters are 250, 470, 1300, and ~10,000.

For each of the three features, the $\log_{10}$ of each value (i.e., LR, LPCb, LL) is determined and then the median of the feature values (LMed) is divided into each cluster's value for that feature. Finally, all three of the factors are added for the final the Cluster Factor (e.g., for C840 the Cluster Factor is calculated as 1.1 + 0.9 + 0.9 = 2.9).

2.3 Modify Initial Top 100 List to Create Interim Top 50 List – A Change of Plans

As stated earlier, the two ways the top 100 object list was planned to be modified was by (1) inclusion in "hot spots" (i.e., adding the Cluster Factor for cluster in which they reside) and (2) identify coupling of objects whose risk is a significant amount of its total risk (i.e., two "paired" objects will become a pair on the Top 50 List rather than individual entries).

However, the research team noted all objects in Tab. 1 were part of the first three clusters. In addition, the cluster factor was so small and provided little differentiation between these clusters as to have little effect on the resulting top 50 list. The "hot spot" analysis included two major features: total risk of cluster is empirical while "PCb" 2025 values are derived statistically. In addition, the coupling effects, as envisioned, were focused largely on empirical results. There was a need to integrate more

Table 2. The cluster factor for each of the four "hotspots" is a function of total risk, "PC by" 2025 (PCb), and persistence; C975 has the largest "cluster factor". This cluster factor is used to adjust the original risk score by being added to it.

Cluster	Altitude Span, km	# Objects/ Ave Mass, kg	Total Risk, kg		"PC by" 2025, %		Persistence, yrs		**Cluster Factor**
			Risk/LR	LR/ LMed	PCb/ LPCb	LPCb/ LMed	Life/LL	LL/ LMed	
C775	700/810	145/1,519	1,075/3.0	1.0	7/0.9	1.1	240/2.4	0.8	**2.9**
C840	810/890	91/3,202	1,461/3.2	1.1	5/0.7	0.9	470/2.7	0.9	**2.9**
C975	890/1100	350/1,280	890/2.9	1.0	26/1.4	1.8	1300/3.1	1.1	**3.9**
C1450	1100/1600	113/1,355	56/1.8	0.6	0.5/-0.3	-0.4	10,000/4.0	1.4	**1.6**
Log_{10} of Median			983/3.0		6/0.8		885/2.9		

statistical features in the analysis and not over-emphasize empirical findings, so this cluster factor was removed from the ranking criteria for now. The authors will discuss inclusion of parts of the cluster factor in the future. Further, the filter of the 700/700 Rule is a much more important parameter to adjust in order to create meaningfully different top 50 lists. Since the 25-yr guideline for post-mission disposal is globally accepted and the orbital lifetime of an intact space objects exceeds 25 yr if it resides above 615 km, a 700/615 Rule was decided upon as an alternate filter. The 25-yr orbital lifetime was determined using an average solar activity and an area-to-mass ratio of 0.01 m^2/kg.

Lastly, there was concern on the team emphasizing short-term empirical collision risk too much over statistical collision risk. As a result, the team decided to apply one more filter in unison with the 700/615 Rule. A new feature is to eliminate any objects involved in fewer than 50 conjunctions within this three-year analysis period. This approach assures objects involved in only a few high-PC events are not given undue ranking especially due to the uncertainty in PC calculations as miss distance starts to approach hard body radius. This new constraint provides more weighting to statistically significant object dynamics. As a result, the final filter for a second interim top 50 list will apply the 50/700/615 Rule. Tab. 3 details the results of the 50/700/615 Rule that can be contrasted with the 700/700 Rule Top 50 List in Tab. 1. This paper considers the 50/700/615 Rule list as the preferred one. However, research will continue during 2025 to finalize an official 2025 Top 50 List planned for release at the International Astronautical Congress.

3. COMPARISON TO ORIGINAL TOP 50 LIST

The two Interim Top 50 lists are similar in composition to the 2020 Top 50 List [5]; Tab. 4 depicts a variety of comparison statistics.

Table 4. Comparing the 2020 Top 50 list with the new interim Top 50 lists for 2025, the primary demographics have not changed drastically.

Top 50 List Demographic	2020 Top 50 List	2025 Interim Top 50 List 0/700/700 Rule	2025 Interim Top 50 List 50/700/615 Rule
Rocket Bodies	39	36	42
Payloads	11	14	8
In the 2020 List	50	20	22
Average Mass	~5,150	~4,610	~5,150
Before 2000	40	38	34
2000 and later	10	12	16
Russia	42	37	32
Japan	4	2	3
Europe	3	1	2
PRC	1	8	11
US	0	2	2
Below 700 km	1	0 by filtering	4
C775	4	11	16
C840	30	19	24
C975	15	20	5
C1400	0	0	1

Table 3. The Interim Top 50 list using the 50/700/615 Rule is significantly different by specific object than the 700/700 Rule list but their demographics are similar.

#	Object Name/SATNO	Risk, kg	Count	Mass, kg	Ave Alt, km	Incl, deg	Launch
1	28353 (SL-16 R/B)	283	341	9000	844	71	2004
2	37766 (CZ-2C R/B)	175	105	4000	663	98	2011
3	27386 (ENVISAT)	175	276	8211	762	98	2002
4	19120 (SL-16 R/B)	117	366	9000	827	71	1988
5	24279 (H-2 R/B)	115	133	2700	1082	99	1996
6	39203 (CZ-2C R/B)	107	142	4000	705	98	2013
7	22565 (COSMOS 2237)	106	64	3200	851	71	1993
8	19650 (SL-16 R/B)	71	262	9000	839	71	1988
9	22823 (SPOT 3)	59	67	1869	826	99	1993
10	44548 (CZ-2D R/B)	55	225	4000	757	98	2019
11	16511 (SL-8 R/B)	52	51	1435	978	83	1986
12	11511 (SL-8 R/B)	50	89	1435	765	74	1979
13	20625 (SL-16 R/B)	48	344	9000	843	71	1990
14	25407 (SL-16 R/B)	46	323	9000	839	71	1998
15	24298 (SL-16 R/B)	44	280	9000	851	71	1996
16	8344 (SL-8 R/B)	43	117	1435	758	74	1975
17	25400 (SL-16 R/B)	40	331	9000	805	99	1998
18	17590 (SL-16 R/B)	40	348	9000	835	71	1987
19	16012 (SL-8 R/B)	40	83	1435	767	74	1985
20	39261 (CZ-4C R/B)	33	168	2000	779	99	2013
21	23774 (SL-8 R/B)	33	63	1435	975	83	1996
22	22566 (SL-16 R/B)	30	293	9000	842	71	1993
23	22220 (SL-16 R/B)	30	330	9000	836	71	1992
24	16182 (SL-16 R/B)	28	359	9000	837	71	1985
25	23705 (SL-16 R/B)	28	331	9000	841	71	1995
26	23405 (SL-16 R/B)	27	364	9000	841	71	1994
27	22803 (SL-16 R/B)	26	341	9000	835	71	1993
28	39014 (CZ-4C R/B)	25	71	2000	995	63	2012
29	28480 (CZ-2C R/B)	25	135	4000	803	98	2004
30	41858 (CZ-2D R/B)	24	242	4000	769	99	2016
31	28931 (ALOS)	24	110	4000	668	98	2006
32	17974 (SL-16 R/B)	22	354	9000	834	71	1987
33	26070 (SL-16 R/B)	22	298	9000	840	71	2000
34	22285 (SL-16 R/B)	22	341	9000	841	71	1992
35	29499 (METOP-A)	20	60	4086	651	98	2006
36	4589 (SL-8 R/B)	19	95	1435	749	74	1970
37	23088 (SL-16 R/B)	19	342	9000	843	71	1994
38	54236 (CZ-6A R/B)	18	64	5800	862	99	2022
39	31793 (SL-16 R/B)	17	304	9000	843	71	2007
40	31114 (CZ-2C R/B)	17	205	4000	825	98	2007
41	17973 (COSMOS 1844)	16	51	3200	844	71	1987
42	10121 (SL-8 R/B)	16	79	1435	768	74	1977
43	22802 (COSMOS 2263)	15	54	3200	847	71	1993
44	19770 (SL-8 R/B)	15	100	1435	759	74	1989
45	16613 (SPOT 1)	14	51	1869	663	99	1986
46	32063 (CZ-4B R/B)	12	98	2000	720	98	2007
47	20491 (H-1 R/B)	12	62	1800	1248	99	1990
48	9023 (SL-8 R/B)	12	114	1435	756	74	1976
49	11427 (SL-8 R/B)	11	92	1435	763	74	1979
50	20791 (CZ-4 R/B)	11	73	2000	918	99	1990

Rocket bodies continue to dominate, no matter which top 50 list is considered. The slight increase in the rocket bodies comes primarily from new Chinese rocket bodies. The US now has two objects in the top 50 list due to two non-operational Spot satellites.

As a matter of fact, only two countries had more objects in the new top 50 list compared to the original – the US and China. Japanese and European objects changed very little. The one constant across all the lists is the SL-16 R/Bs in Cluster 840.

The cluster with the highest PC by 2025 (i.e., Cluster 975) had a marked decrease in members for the last top 50 list (i.e., 50/615/700); the 15-object decrease was evenly spread across the lower three regions (i.e., between 615 and 700 km, Cluster 775, and Cluster 840).

The new top 50 list included more recently abandoned (i.e., after the year 2000) objects than the original top 50 list. Most of the overlapping 20 and 22 objects in the two interim respective top 50 lists and on the original top 50 list are SL-16 R/Bs.

4. OTHER ISSUES OF TARGET SELECTION

The examination of coupling affecting results of the top 50 list was postponed, however, it is likely that elimination of objects involved in fewer than 50 conjunctions will reduce the effects of coupling. When the research team assessed pairs that appeared to be "coupled" it was found in objects with very few high PC conjunctions but with high aggregate risk.

Further, Cluster 840, while having many massive intact derelict objects, also has the peak spatial density of fragments. As a result, there is a significant cumulative probability of low intensity collisions (i.e., cataloged fragments striking massive derelict objects) that may need to be considered in the evaluation of objects on the Top 50 list.

ADR targets in similar inclinations may be relevant for consideration in "moving up the list" as it has been shown in ADR mission simulations when multiple objects are removed, the return on investment is much more pronounced [11]. Since moving between orbits with similar inclinations using J_2 gravitational effects is easier [12], it might be relevant to adjust or partition the list by this parameter characteristic.

From a propulsive perspective, considering C775 and C840 altitude spans as the most critical, it is as easy to change altitude by 250 km as it is to change inclination by only one degree[1].

Rocket bodies are easier to grapple than payloads since they all have a rocket nozzle to which a grappler may attach a fixture, whereas payloads may have greatly different configurations that may complicate their removal. For this reason, rocket bodies might be assigned a preferential order on a top 50 list.

The primary focus of identifying the members of the top 50 list is their collision risk. However, in noting the large number of rocket bodies on the list and the large number of rocket bodies that have exploded in the past the factor of explosion likelihood should be examined carefully.

In examining the top 10 breakups due to accidental explosions, five are from R/Bs [1]. Four of these exploded within five years of launch, and two have occurred since 2000. These are the CZ-6A explosions in Aug 2022 and Nov 2024.

Some of the largest fragmentation events occurred decades ago, but due to high persistence from a high breakup altitude, many fragments still remain in LEO. For example, the Delta 1 R/B abandoned in 1975 fragmented in 1991 at 1100 km and over 73% of the +300 fragments generated are still in orbit.

Further, the top 75 breakup events account for 90% of all fragments currently in LEO. Accidental R/B explosions account for 26 of these events and comprise nearly 40% of all fragments in LEO.

Breakup events for derelict rocket bodies (or even spacecraft) have been studied for some time. In general, the hazards can be classified as either propulsion/propellant-related, or battery-related.

In each case, the hazard is stored energy which can be released in a violent manner causing the generation of many fragments.

For more than a decade, NASA and other agencies have been establishing standards to mitigate debris generation. One of these, NASA-STD-8719.14C, is focused on the passivation of an upper stage after it completes its mission. It states that passivation can be achieved by either:

1. *"…deplete all onboard sources of energy and disconnect all energy sources…"*
2. *"…control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft."*

Since the first statement is rather absolute, it is unlikely to be achievable in most practical cases leading to an approach that tends toward the second statement.

[1] This calculation was completed for a starting orbit of 800 km circular orbit.

This means for most upper stages items such as residual amounts of hypergolic propellants, energy storage batteries, and even potentially helium pressurant remain. The location, condition and sensitivity of these remaining energetic materials are the factors that must be considered when examining remediation strategies. Many of the worst upper stages on the top 50 list were abandoned before debris mitigation standards were proposed and implemented. These may have even larger quantities of potentially hazardous materials remaining aboard. The Tab. 5 below shows a summary of the types of upper stages with the propellants used on each.

The greatest concern for a debris generating event would typically be for hypergolic propellant combinations (UDMH/N_2O_4) because these can be susceptible to either propellant or oxidizer migration past degraded seals, resulting in a detonation or deflagration with sufficient energy to cause breakup of the vehicle. However, even for those stages that use non-hypergolic propellants, there are potential energetic materials such as batteries or hydrazine for settling thrusters. It should also be noted that even for stages where passivation has occurred, the threat of a fragmentation event due to battery breakdown still may exist.

When the first top 100 list was generated based purely on risk for this paper, there were many fragments included. Though it was decided to remove these fragments from consideration as “objects to be targeted for ADR,” their distribution is interesting. Looking at the top 50 fragments filtered out of the original top 100 list, they were spread out from being #4 on the list with an aggregate risk of ~156 kg to #96 on the list with an aggregate risk of ~93 kg. The six most populous fragment clouds of these 50 objects are:

- Feng-yun 1C (16 fragments);
- NOAA 16 R/B (six fragments);
- Cosmos 2251 (six fragments);
- Delta 1 R/B (four fragments);
- DMSP 5D-2 F13 (three fragments);
- CZ-4 R/B (three fragments).

The Feng-yun 1C fragment cloud is still the largest in LEO and it originated near the center of C840, so it is not a surprise it has the most fragments posing a significant debris-generating potential in LEO.

The NOAA 16 fragment cloud originated very near where the Feng-yun 1 C breakup was centered.

The authors still believe, despite their high empirical aggregate risk, fragments should not be the primary or initial objects targets for ADR operations.

5. CLOSING OBSERVATIONS

It is important to note the coauthors abide by the philosophy that there are many viable models to derive the top 50 objects to be considered for removal from LEO.

The benefit of the current method was to apply a team approach to adjusting filters to a single model, however, the implication is not that this model is the only way to select the top 50 objects.

In essence, one of the most critical aspects of any attempt to identify the objects whose retrieval will decrease the debris-generating potential in LEO is to identify key features of objects to be removed such as type, mass, probability of collision (especially with other massive objects), inclination, altitude, etc.

The research team is continuing to refine the top 50 list with trade studies examining alternatives to the 50/615/700 Rule and how to incorporate coupling and “hot spots”.

This Interim Top 50 list may indeed remain intact after further investigation, however, due to the likelihood this artifact will be used widely it is critical to examine all issues very carefully and methodically.

An updated final top 50 list will be presented at the International Astronautical Congress.

Table 5. Propellant Combinations of Selected Derelict Rocket Bodies

Upper Stage Type	Propellant (Fuel)	Propellant (Oxidizer)
CZ-2D	UDMH	N_2O_4
SL-12	UDMH	N_2O_4
SL-14	UDMH	N_2O_4
SL-16	RP-1	O_2
CZ-6A	RP-1	O_2
H-II Second Stage	H_2	O_2
Centaur	H_2	O_2

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Appendix A. Original Top 100 List (before filtering objects smaller than 700 kg and objects lower than 700 km).

#	SATNO (Object Name)	Risk, kg	Count	Mass, kg	Ave Alt, km	Incl, deg	Launch
1	28353 (SL-16 R/B)	283	341	9000	844	71.00	2004
2	37766 (CZ-2C R/B)	175	105	4000	663	98.16	2011
3	27386 (ENVISAT)	175	276	8211	762	98.32	2002
4	34079 (IRIDIUM 33 DEB)	156	12	0.5	651	86.39	1997
5	25418 (ORBCOMM FM 15)	150	17	40	766	45.00	1998
6	7727 (COSMOS 724)	135	25	3769	897	65.59	1975
7	17543 (ARIANE 1 DEB)	130	12	0.5	849	98.53	1986
8	31196 (FENGYUN 1C DEB)	129	23	0.5	811	98.54	1999
9	41085 (NOAA 16 DEB)	129	22	0.5	819	98.72	2000
10	19120 (SL-16 R/B)	117	366	9000	827	71.01	1988
11	24279 (H-2 R/B)	115	133	2700	1082	98.70	1996
12	21368 (DELTA 1 DEB)	113	9	0.5	1038	99.49	1975
13	39203 (CZ-2C R/B)	107	142	4000	705	98.38	2013
14	22565 (COSMOS 2237)	106	64	3200	851	70.80	1993
15	30943 (FENGYUN 1C DEB)	99	23	0.5	880	98.82	1999
16	5917 (METEOR 1-11)	94	33	1200	862	81.22	1972
17	16292 (SL-8 R/B)	86	33	1435	974	82.93	1985
18	28060 (SERVIS 1)	86	11	840	992	99.48	2003
19	19650 (SL-16 R/B)	71	262	9000	839	71.00	1988
20	15986 (COSMOS 1677)	60	19	3769	940	64.68	1985
21	36123 (CZ-4C R/B)	60	37	2000	1086	100.52	2009
22	22823 (SPOT 3)	59	67	1869	826	98.93	1993
23	42386 (NOAA 16 DEB)	59	40	0.5	792	98.70	2000
24	24304 (COSMOS 2334)	59	16	820	986	82.93	1996
25	35993 (COSMOS 2251 DEB)	57	25	0.5	687	74.01	1993
26	44548 (CZ-2D R/B)	55	225	4000	757	98.28	2019
27	16511 (SL-8 R/B)	52	51	1435	978	82.95	1986
28	25590 (COSMOS 2361)	51	12	820	988	82.93	1998
29	11511 (SL-8 R/B)	50	89	1435	765	74.03	1979
30	42294 (DMSP 5D-2 F13 DEB)	49	48	0.5	707	98.88	1995
31	20625 (SL-16 R/B)	48	344	9000	843	71.00	1990
32	23603 (COSMOS 2315)	47	14	820	989	82.90	1995
33	25407 (SL-16 R/B)	46	323	9000	839	71.01	1998
34	31560 (FENGYUN 1C DEB)	45	32	0.5	822	98.63	1999
35	24298 (SL-16 R/B)	44	280	9000	851	70.78	1996
36	6019 (COSMOS 489)	43	13	820	978	74.02	1972
37	8344 (SL-8 R/B)	43	117	1435	758	74.06	1975
38	25567 (NADEZHDA 5)	43	17	825	992	82.95	1998
39	25400 (SL-16 R/B)	40	331	9000	805	98.77	1998
40	17590 (SL-16 R/B)	40	348	9000	835	71.00	1987
41	16012 (SL-8 R/B)	40	83	1435	767	74.06	1985
42	39261 (CZ-4C R/B)	33	168	2000	779	98.91	2013
43	23774 (SL-8 R/B)	33	63	1435	975	82.98	1996
44	22566 (SL-16 R/B)	30	293	9000	842	71.01	1993
45	22220 (SL-16 R/B)	30	330	9000	836	71.00	1992
46	29913 (FENGYUN 1C DEB)	29	14	0.5	870	98.78	1999
47	24773 (SL-8 R/B)	29	45	1435	986	82.92	1997
48	16182 (SL-16 R/B)	28	359	9000	837	71.00	1985
49	23705 (SL-16 R/B)	28	331	9000	841	71.02	1995
50	23405 (SL-16 R/B)	27	364	9000	841	70.98	1994

#	SATNO (Object Name)	Risk, kg	Count	Mass, kg	Ave Alt, km	Incl, deg	Launch
51	40605 (DMSP 5D-2 F13 DEB)	27	29	0.5	734	98.65	1995
52	10531 (COSMOS 970)	27	13	2000	1036	65.85	1977
53	21512 (DELTA 1 DEB)	26	8	0.5	1108	99.94	1975
54	22803 (SL-16 R/B)	26	341	9000	835	70.99	1993
55	57831 (CZ-6A R/B)	25	12	5800	801	85.99	2023
56	30656 (FENGYUN 1C DEB)	25	29	0.5	765	99.00	1999
57	39014 (CZ-4C R/B)	25	71	2000	995	63.39	2012
58	28480 (CZ-2C R/B)	25	135	4000	803	98.19	2004
59	41858 (CZ-2D R/B)	24	242	4000	769	98.62	2016
60	28931 (ALOS)	24	110	4000	668	98.07	2006
61	17974 (SL-16 R/B)	22	354	9000	834	71.01	1987
62	26070 (SL-16 R/B)	22	298	9000	840	71.00	2000
63	22285 (SL-16 R/B)	22	341	9000	841	71.02	1992
64	21088 (SL-8 R/B)	21	42	1435	973	82.94	1991
65	20895 (CZ-4 DEB)	21	9	0.5	710	98.36	1990
66	29499 (METOP-A)	20	60	4086	651	98.34	2006
67	13114 (SL-14 R/B)	20	36	1407	947	82.54	1982
68	39679 (SL-4 R/B)	20	86	2355	483	51.61	2014
69	34007 (COSMOS 2251 DEB)	20	10	0.5	689	74.02	1993
70	12319 (COSMOS 1249)	20	27	3769	940	64.97	1981
71	4708 (THORAD AGENA D DEB)	20	8	0.5	939	100.06	1970
72	4589 (SL-8 R/B)	19	95	1435	749	74.06	1970
73	40057 (VELOX 1)	19	7	4.3	595	98.31	2014
74	23088 (SL-16 R/B)	19	342	9000	843	71.00	1994
75	10676 (COSMOS 990)	18	49	820	768	74.04	1978
76	205 (TRAAC)	18	14	105	1027	32.44	1961
77	54236 (CZ-6A R/B)	18	64	5800	862	98.84	2022
78	33789 (COSMOS 2251 DEB)	18	10	0.5	935	74.06	1993
79	4784 (SL-8 R/B)	17	36	1435	975	74.03	1970
80	31793 (SL-16 R/B)	17	304	9000	843	70.98	2007
81	29998 (FENGYUN 1C DEB)	17	25	0.5	802	99.34	1999
82	29894 (FENGYUN 1C DEB)	17	6	0.5	962	99.52	1999
83	31114 (CZ-2C R/B)	17	205	4000	825	98.36	2007
84	26262 (CZ-4 DEB)	17	11	0.5	655	98.36	1999
85	17973 (COSMOS 1844)	16	51	3200	844	70.90	1987
86	42556 (DELTA 1 DEB)	16	30	0.5	830	98.50	1972
87	10121 (SL-8 R/B)	16	79	1435	768	74.05	1977
88	30288 (FENGYUN 1C DEB)	16	15	0.5	795	99.41	1999
89	18187 (COSMOS 1867)	16	35	3090	787	65.01	1987
90	22802 (COSMOS 2263)	15	54	3200	847	70.93	1993
91	54971 (CZ-6A DEB)	15	2	0.5	875	98.85	2022
92	19770 (SL-8 R/B)	15	100	1435	759	74.05	1989
93	1529 (DELTA 1 DEB)	14	23	0.5	812	99.05	1965
94	26474 (TITAN 4B R/B)	14	212	4500	550	67.99	2000
95	34854 (COSMOS 2251 DEB)	14	20	0.5	652	74.03	1993
96	41337 (ASTRO H)	14	25	2700	546	31.00	2016
97	16613 (SPOT 1)	14	51	1869	663	98.67	1986
98	32063 (CZ-4B R/B)	12	98	2000	720	98.15	2007
99	20491 (H-1 R/B)	12	62	1800	1248	99.01	1990
100	34022 (COSMOS 2251 DEB)	12	16	0.5	764	74.05	1993

Appendix B: Kinetic Theory of Gases and Poisson Probability Distribution Function Development

λ is the frequency within the Poisson probability density function (i.e., P(k)) taken from the kinetic theory of gases analogy.

$\lambda = AC * VR * SPD$ (1)

$where \quad SPD = N/Vol$ = spatial density, #/km^3

N = number of objects,

Vol = volume, km^3, in which objects reside

AC = collision cross-section, km^2

VR = relative velocity, km/s

Generally, the probability of k events given a frequency, λ, is:

$P(k) = (\lambda^k e^{-\lambda})/k!$ (2)

where λ = expected # of occurrences over time, t

k = number of occurrences (k = 0,1...)

When it is assumed there will be very few events (i.e., the probability of one event is much, much greater than two events, etc.), the probability can be determined by 1 (i.e., the total all possible occurrences) minus the probability of no events. The result is represented by the well-known expression in equation (3).

$P(1) = PC = 1 - e^{-\lambda t}$ (3)

PC is the collision hazard to one satellite from N objects in the population. PC is only concerned with the target, e.g., operational satellite getting hit by cataloged debris.

For a cluster of derelicts we are concerned about collisions between any two of the N objects in the cluster. This is called the collision rate (CR) and is the cumulative PC for N objects on each other. CR is represented by:

$CR = \sum PC = (1/2)\, N\, (AC * VR * SPD * T)$ (4)

$= (N^2/2) * (AC * VR * T) / (Vol)$

{since SPD = N/Vol}

When the encounter dimension (derived from AC where AC = π r^2) is half of the miss distance then the collision rate is equivalent to the encounter rate (ER).

The next logical question is "if we accept the frequency found with a Poisson distribution, when might the first collision occur?" Using a gamma distribution, this can be evaluated for a given confidence level in equation (5).

$\Gamma = -ln(1 - C) * (1/CR)$ (5)

where Γ = # of years until the first event

C = confidence interval

CR is Poisson-derived encounter rate