Research Report

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Comparing the Cost-Effectiveness of Expendable Versus Reusable Small Air Vehicles

The United States has long employed small autonomous air vehicles for a variety of missions. Examples include the ADM-141 TALD (tactical air-launched decoy) and the ADM-160 MALD (miniature air-launched decoy). A well-known case is the use of the BQM-74 and ADM-141 TALD on the opening night of Desert Storm in 1991 to confuse and degrade the Iraqi integrated aerial defense system (IADS) (Cohen, 1993, pp. 127–131). Such small autonomous air vehicles have been used in combat missions in which they were usually not recovered.

The United States has also employed a variety of small unmanned vehicles for reconnaissance purposes, such as aerial photography during the Vietnam War. Such systems in the past have required full or partial recovery. Examples include the recovery of the film pods from a reconnaissance spacecraft or the recovery of the entire system, as was the case with the Vietnam War–era Ryan Model 147 Lightning Bug (Parsch, 2002–2003). Systems or components have been successfully recovered on land, at sea, or midair. These past recovery approaches have been expensive, requiring the use of valuable assets such as helicopters, ships, or specialized aircraft. In addition, recovered systems have often been damaged by landing, by time in salt water, and in other scenarios and have thus not been available for ready reuse. However, more recent use of unmanned aerial vehicles (UAVs) equipped with modern flight control and navigation systems, such

KEY FINDINGS

- The reusable platform is favored by a substantial margin if the conflict requires more than a few sorties.
- Land-based recovery is much less expensive than mid-air recovery.
- The expendable platform is only a desirable solution if the U.S. Department of Defense can be certain that the system will not be used more than a few times over its lifetime, attrition will remain high for long periods of time, or if recovery costs will be quite high.

Abbreviations

DARPA	Defense Advanced Research Projects Agency
FY	fiscal year
IADS	integrated air defense system
lb	pound
MALD	miniature air-launched decoy
UAV	unmanned aerial vehicle

as a Global Positioning System or inertial navigation system, makes it possible to greatly reduce the recovery costs of small aircraft that are less than a thousand pounds.

In this report, we analyze a variety of cases involving small, high-subsonic aircraft that are launched from larger aircraft and employed primarily to support, perhaps as decoys and/or jammers, larger aircraft on high-risk missions. For example, these small aircraft could function as decoys to confuse the threat IADS and/or as jammers to degrade threat radar or passive detection systems. We examine the relative costs of using expendable systems, which the United States has done in the past and does currently with the ADM-160 MALD, and using reusable systems, particularly those that take advantage of current technology to perform autonomous landings. This analysis is particularly appropriate for supporting proposed small reusable aircraft programs such as the Defense Advanced Research Projects Agency's (DARPA's) Gremlin.

Analysis Results

In this chapter, we discuss our analysis and its results. We start with a baseline case, then present excursions that vary the baseline assumptions to gauge the robustness of our results.

Baseline Case

For our baseline case, we examine two air vehicles—an expendable one and a reusable one. Both have a payload of 60 pounds (lbs), conventional airframes, turbofan engines, and a high subsonic cruise speed. Estimated empty weights and costs are derived from a RAND Corporation–developed aircraft design model[1] and historical cost-weight relationships,[2] as shown in Table 1.

The major difference between the two vehicles is the larger size of the longer-range reusable vehicle, which, based on our best engineering judgment, includes a 2 percent higher cost and weight penalty for adding the landing gear. We assumed that the reusable aircraft has limited reliability. Therefore, in addition to attrition as a result of enemy action, we assumed a reusable aircraft has system failures equivalent to a 1 percent chance of total system loss.

Another large difference in overall system costs is the reusable system's requirement for a recovery crew. We assumed that a crew of two enlisted personnel equipped with one vehicle can recover four systems per day. We also assumed a representative personnel average cost of $50,000 per person per year (in constant fiscal year [FY] 2018 dollars) for 30 years.[3] That is, even if the crew only performs one recovery in the 30-year lifetime of the system, we included the full 30-year cost of maintaining personnel and recovery equipment in peacetime readiness. This cost is an important driver of the results of the analysis. Were we to only include the marginal costs of recovery, as opposed to the dedicated recovery team sustainment cost, reusable aircraft costs would be much lower. Note that we assumed that the aircraft conducts a fully automated landing so that the primary task of the recovery crew is physically recovering the landed aircraft. If the recovery crew had to actively fly and land the aircraft, the costs would be higher.

We further assumed that recovery takes place at a location separate from, but near to, the operating base that employs the other aircraft in the operation. And we assumed that the reusable aircraft flies one sortie every two days to allow time for refurbishment and repositioning of the UAVs. In our baseline assumptions, reusable aircraft suffer an attrition rate of 1 percent per sortie and an additional

[1] Model details can be found in Xu et al., 2016.

[2] Specifically, we have assumed $2,600 per pound for the 60-lb payload, and $1,300 per pound for 30 lbs of flight avionics for the structure, engines, and similar components.

[3] These assumptions are for rough costing. A real recovery unit would have a variety of grades and jobs.

TABLE 1

Comparison of Two Small Aircraft in Baseline Case

Type of Small Aircraft	Payload (lbs)	Empty Weight (lbs)	Range (nautical miles)	Flyaway Cost
Expendable	60	130	470	$364,000
Reusable	60	230	1,200	$496,000

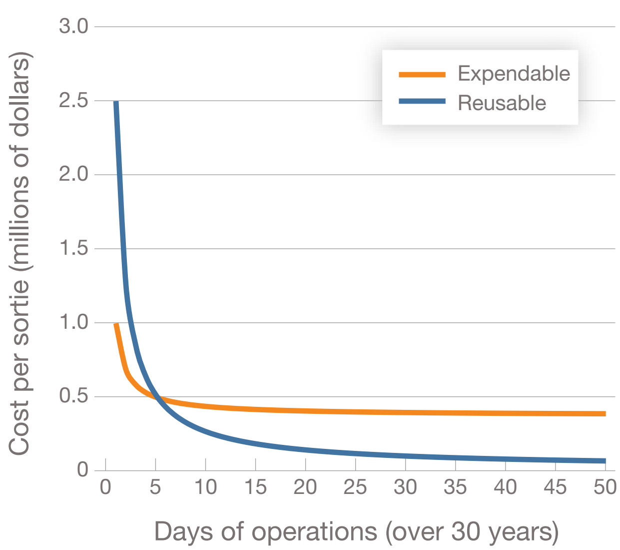
refurbishment and repair cost estimated at approximately 1 percent of the aircraft's procurement cost based on the author's best engineering judgment. In practice, the repair of the damage from flight and recovery would include both the refurbishment unit personnel labor cost and the material cost of spare parts needed. A complete list of assumptions appears in the appendix.

Figure 1 presents the cost per sortie for the expendable and reusable platforms as a function of the number of sorties flown in the system's (30-year) lifetime for the baseline cases. The orange line is data for the expendable platform, and the blue line applies to the reusable platform.

The shape of the curve is a function of the fact that there are two fundamental types of costs: costs—such as procurement, training, and 30-year sustainment costs—that accrue simply by possessing the system and costs that increase as the system is used more, especially the costs of replacing or repairing lost or damaged aircraft. If the system is only used once in combat in its lifetime—the leftmost point on the two curves—the reusable is much more expensive ($1,000,000 for the expendable one versus $2,500,000 for the reusable one) primarily because the entire net present value of the reusable's recovery personnel over 30 years is charged to the one mission. Simply put, there is no point in spending money to procure a reusable system if it is not going to be reused.

FIGURE 1

Cost per Sortie, by Number of Lifetime Sorties for Baseline Case



However, if the system is used more than five times over a 30-year lifespan, the cost of the expendable system is higher (as shown in Figure 1), primarily because of the necessity of replacing the flight articles after every use. Five reuses are sufficient to pay for the net present value of the recovery crew over 30 years and the more expensive reusable air vehicle.

Both curves flatten out toward the right. If there are many sorties over the system's lifetime, the cost per sortie is dominated by the marginal cost of additional sorties because the upfront cost of the system is spread out over its many uses.

The key reason that the reusable system is cheaper over the long run is that the marginal cost of recovering and refurbishing a reusable aircraft is much less than the marginal cost of procuring an expendable aircraft replacement. The marginal cost does not include the 30-year personnel cost of the dedicated recovery capability, which is included in the upfront cost; it only includes the marginal cost of employing it. Most of the cost is in the spare parts necessary for the repair and refurbishment of damaged reusable flight articles. Even if this cost were much higher than the 2 percent loss rate we assumed, it would be less than the cost of replacing the entire system.

This is the key finding of this report. To examine the robustness of this conclusion in the face of uncertainty, we next show excursions measuring the dependence of this result on variations in the assumptions. Most of the excursions do not change the nature of the basic result. However, there is an exception in the case of midair recovery, which appears to be a very expensive option.

Excursions

Here, we examine a number of excursions off the baseline case, starting with vehicle size, then sensitivity to vehicle cost estimates, midair recovery, changes in attrition assumptions, and changes in program lifetime.

Vehicle Size

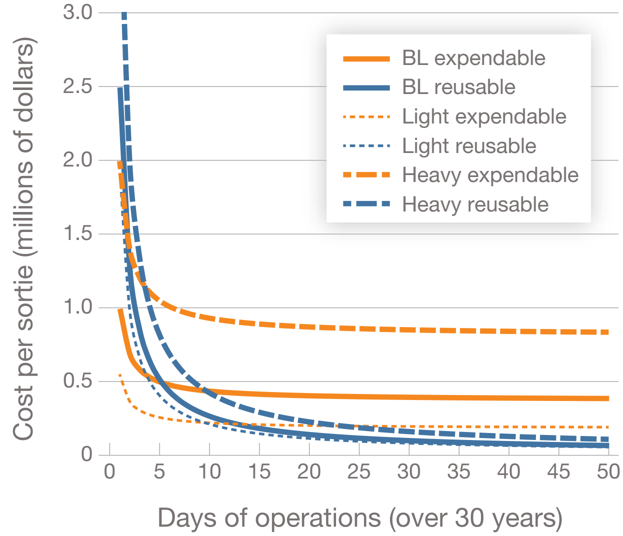
Our baseline case considered an aircraft with a 60-lb payload. The nature of the payload does not enter into our analysis, but the size suggests a jamming or spoofing capability or perhaps simple electronic intelligence. We consider cases with no payload, systems operating as pure decoys, and systems with a significantly larger 200-lb payload, perhaps carrying a substantial intelligence, surveillance, and reconnaissance capability or even lightweight weapons.

Figure 2 presents the same comparison as in Figure 1, but for three different sizes of payload (0, 60, and 200 lbs). The solid orange and blue lines show the same data as in Figure 1. In Figure 2 and the figures that follow, we use orange lines to indicate data for expendable systems and blue lines of the same style for systems that are similar but reusable.

The dashed lines show data for a heavier air vehicle, and the dotted lines show data for a lighter one. Overall, the general result is the same. Reusable solutions are better if they are, in fact, reused. There is a change in the crossover point—the number of reuses at which the reusable system becomes more cost-effective. The heavier and more expensive the vehicle, the greater the value in reusing it. In other words, the crossover point shifts left toward fewer lifetime uses.

A key cost is the *marginal* cost of recovery. This is relatively low in our baseline. But in the extreme case in which the flyaway cost of the aircraft is also very low, expendable systems make sense even if they fly a large number of sorties. In our model, this works out to an empty vehicle weight of about 10 lbs. However, the feasibility of building something that small that can perform a useful military mission is questionable and is beyond the scope of this study.

FIGURE 2
Excursions with Lighter and Heavier Empty-Weight Air Vehicles



NOTE: BL = baseline.

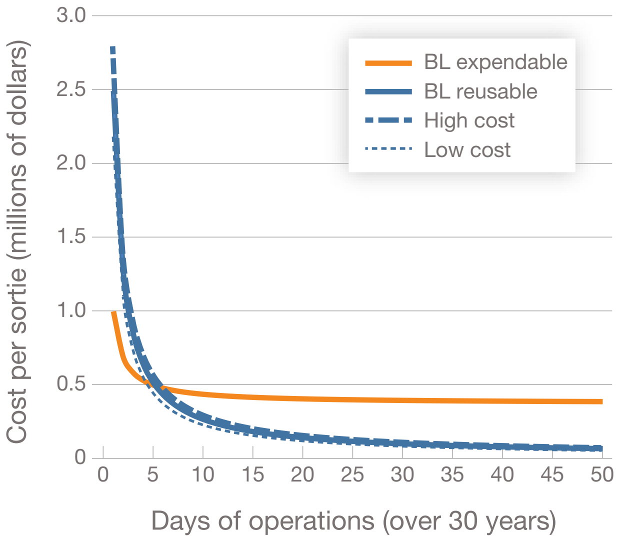
Sensitivity to Vehicle Flyaway Cost Estimates

In another excursion, we considered the extent to which our conclusions were a result of our particular assumptions about vehicle flyaway cost. Suppose we were wrong by a large factor. In our baseline case, we used standard aircraft conceptual design tools and estimated that the cost premium for producing longer-range reusable aircraft is to add 36 percent to the average flyaway cost of the expendable. But what if the cost premium for longer range was twice as high? And what if the cost premium was zero—that we could build longer-range aircraft with no additional increase in flyaway cost at all? We have no reason to believe that our assumption of higher flyaway costs for longer-range aircraft is wrong, but what if it is? How much would it matter?

Figure 3 shows cases in which the additional flyaway cost of a reusable aircraft is estimated to be twice as high as our baseline—72 percent—or is estimated to be simply the same as the shorter-range aircraft. The solid orange line for the expendable aircraft is the same as in the previous figures. The three blue lines are the baseline (solid) for the reusable and

FIGURE 3

Excursions in Cost Estimates for Reusable Aircraft



two excursions (dashed and dotted) off the baseline. Substantial variations in the cost-model inputs used for estimating for the reusable aircraft costs clearly make very little difference to the results of the analysis. The implication is that if the estimated empty-weight inputs for the cost model of platform costs are wrong, or the weight-based estimates of flyaway costs are uncertain, it does not change the overall picture appreciably.

Figures 2 and 3 lead to an interesting conclusion. If we are committed to an expendable concept, holding down the weight and associated flyaway cost of the vehicle is all-important. If, however, we are employing a reusable platform, adding capability, even if it means higher weight and flyaway cost, may not have a large impact on overall system costs per sortie, which are dominated by the recovery personnel costs of the reusable system. Thus, these costs are the important ones to control for small reusable aircraft.

Midair Recovery

An alternative to ground recovery is to recover the system midair. We have used our methodology to estimate costs for such a recovery system. For this analysis, we assumed that one C-130 can recover four small aircraft per day. While the United States has long used aircraft to recover parachuting objects such as film containers, recovering a flying object presents different challenges.[4] We do not examine these technical and operational challenges here and do not consider them for this excursion analyzing onboard specialized recovery systems and estimating the costs of developing, procuring, and sustaining the specialized equipment and training the crew necessary for midair recovery of reusable aircraft. We only include costs for employing a generic C-130 for midair recovery of reusable aircraft. We assume the recovering aircraft (generic C-130) operates during both wartime and peacetime training operations with zero attrition. Nevertheless, the costs of midair recovery are extremely high, primarily because of the 30-year ownership costs, including procurement, peacetime operations, and maintenance of the required C-130.

We assumed the following as part of the analysis:

- C-130 recovers four air vehicles per day.
- Procuring the recovery system costs $16,825,000 ($67,300,000 for the C-130 divided by four).
- Recovery system operations and support is $1,935,500 per year over 30 years ($7,7420,000 per year for C-130 divided by four).
- We included no costs for specialized recovery equipment or additional C-130 recovery team training.[5]

Figure 4 compares the cost of midair recovery with the cost of land-based recovery and expendable systems. We changed the vertical scale in this chart to accommodate the significant costs of midair recovery. The solid lines show the same data as in previous charts, but they are plotted logarithmically, while the blue dashed line is the cost for midair recovery. As the figure makes clear, the cost of midair recovery is proportionally much higher than land recovery.

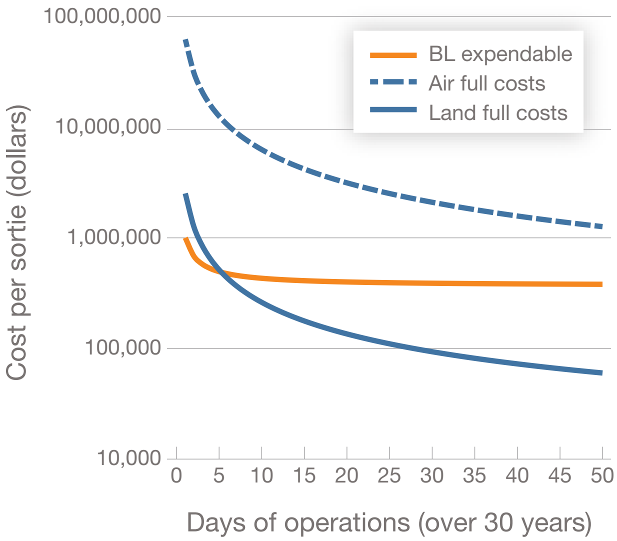
In another excursion, we looked at the cost for midair recovery, assuming that the only costs to the Department of Defense are the marginal costs of C-130 operations. This excursion assumes that

[4] DARPA's Gremlin program is current moving toward flight tests of a C-130–based airborne recovery system.

[5] C-130 costs are from the Air Force Total Cost of Ownership database and are for a C-130J assigned to the tactical airlift mission within Air Mobility Command.

FIGURE 4

Cost Comparison of Expendable with Air and Land Recovery for Reusables



all of the peacetime costs of procurement, operations, and training for the use of recovery systems are accounted for and funded by another entity. In particular, we assumed that not only the basic C-130 aircraft but also procurement of unique equipment, specifically for the midair recovery reusable UAV mission, would be available at no cost. We also assumed that crews skilled in midair recovery would be trained, and that the equipment would be maintained in peacetime by another organization. In effect, wartime C-130s and appropriately trained crews are available at no cost other than the marginal costs of operations, such as fuel. This analysis is *not* consistent with sound accounting principles or with U.S. law (10 U.S.C. § 2434) regarding cost estimates. Nevertheless, we can compute the numbers, even though we do not believe them to be a sound basis for decisionmaking.

For this particular excursion, we assumed the following:

- All recovery equipment is available with no procurement cost.
- There are no peacetime training or sustainment costs associated with recovery.
- There are no costs from wartime deployment.
- The only costs are marginal per-hour costs of actual combat operations: six flying hours per wartime operation at a C-130 cost of $13,644 per hour (Air Force Total Ownership Cost cost per flying hour) and, for the land-recovery cases, land recovery crew at $100 per hour per individual.

Figure 5, which also uses the logarithmic scale of Figure 4, plots the data from Figure 5 with the data from the marginal-cost cases for air and land recovery. Only considering marginal costs reduces the cost of the air recovery option enormously—by a factor of ten. Our breakeven point moves from five days in the baseline to ten days with the air recovery, with only marginal costs. While the ground recovery is still favored, the difference is much smaller.

Although we do believe these marginal cost assumptions to be inappropriate, we present the results to demonstrate the great importance of careful analysis of the peacetime cost of any proposed reusable system. Inappropriate cost assumptions can lead to seriously misleading results.

Attrition Assumptions

In our baseline case, we assumed that a reusable air vehicle flies with a wartime attrition rate of 1 percent. We now consider the effect on the analysis of changes in that assumption, especially cases in which the attrition is much higher, as they easily could be in high-risk missions. We hold the 1-percent damage rate constant, as it is assumed to occur during recovery and not in combat. Figure 6 adds to our previous analysis cases, in which the wartime attrition rate is increased from 1 percent to 25 percent and 65 percent.

We see that an increase of the attrition rate to 25 percent per sortie (the dashed blue line) does not greatly change the basic results. The reusable platform is more expensive, but still preferred over the expendable platform if the system will have more than about eight uses.

At an attrition rate of 65 percent per sortie (the blue dotted line), the costs of the reusable and expendable vehicles are the same if the system is employed for more than 50 days. The cost of replacing the cheaper expendable 100 percent of the time matches the cost of replacing the more expensive reusable 65 percent of the time. If the attrition rate

FIGURE 5

Full and Marginal Cost Recovery for Air and Land Recovery

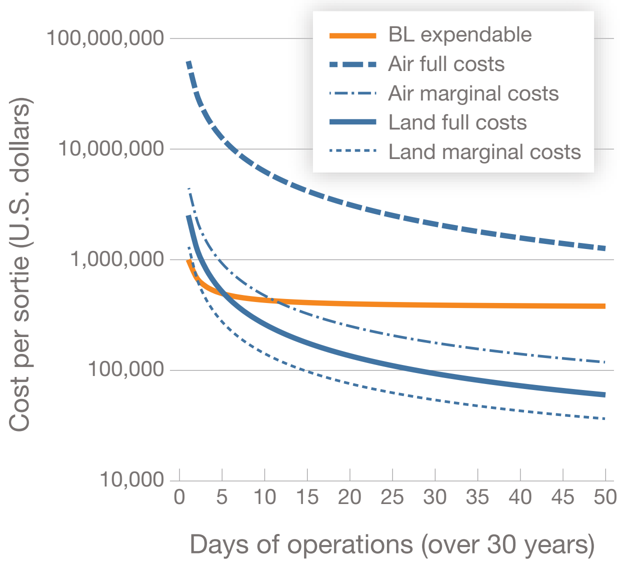
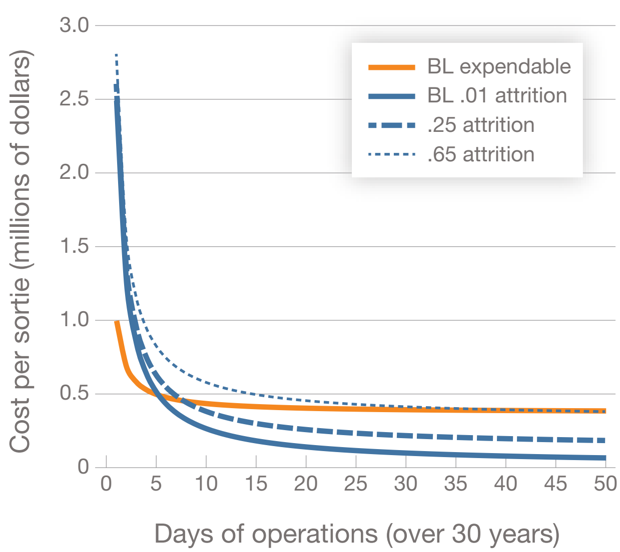


FIGURE 6

Cases with Greatly Increased Wartime Attrition



were even higher, the expendable would be favored over the reusable. Logically, there is no point in spending money on a reusable aircraft if it is unlikely to survive a single mission.

We also consider a case in which the attrition is variable—90 percent on the first day of the conflict and decreasing to 1 percent linearly over 14 days. This attrition decrease might be observed in a scenario in which the United States succeeds in drawing down the enemy IADS during the first two weeks of the conflict, thus enabling subsequent air operations to proceed in a more benign environment. Such a sequence of events is consistent with U.S. doctrine and extensive campaign modeling.

Figure 7 shows the cost per sortie for this case, along with our baseline. The results are intuitive: If the conflict ends before the attrition level drops significantly below 65 percent, the expendable system is preferred. If there are a significant number of days of combat with less than very high attrition, the reusable is preferred.

One suggested alternative is a hybrid strategy, in which the United States procures both expendable and reusable platforms and employs them depending on the expected attrition on any particular day of the war.

Using the same linearly decreasing attrition rate as the previous case, Figure 8 examines the cost per sortie of a concept of employment in which the Blue team employs expendable aircraft at the outset of the conflict, switching to reusable aircraft when the attrition rate falls below 65 percent—the threshold where, in the long run, the reusable becomes cheaper. The data are the same as in the previous chart, with the addition of the dotted blue line to represent the mixed-force case. The dotted blue line is difficult to discern, as it falls almost entirely on the dashed blue line for the purely reusable case.

Figure 8 shows that the mixed-force result is almost identical to the cost of the pure reusable case. There are some small savings from employing the less expensive platforms in the opening days of the conflict. However, the overall cost of the reusable platform, which is dominated by the peacetime cost of the recovery and refurbishment system, is almost the same. The point is that once the cost of procurement, training, and 30-year sustainment for the reusable fleet has been paid, using it for fewer days saves very little.

This analysis assumed that there are no costs associated with developing and maintaining two different systems and deciding which to deploy on any given day. We assumed that the Blue team has perfect information about future attrition and can use that

FIGURE 7
Cost per Sortie in Case with Varying (Decreasing) Attrition

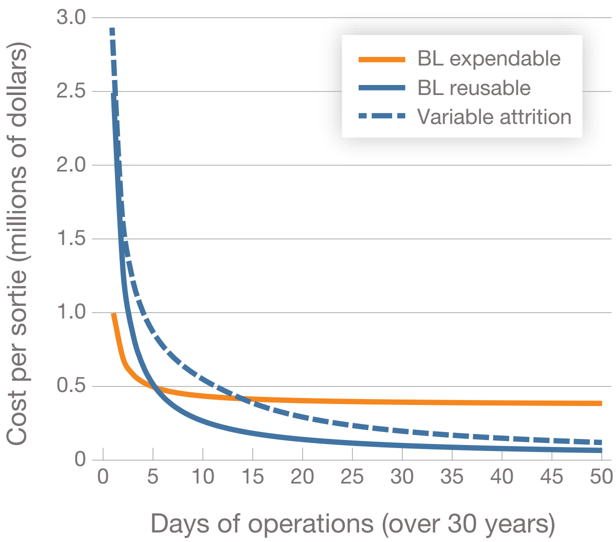
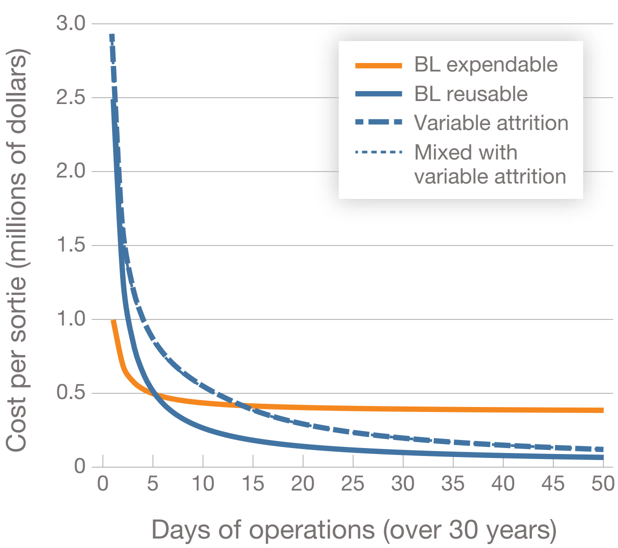


FIGURE 8
Comparison of a Mixed Force with Pure Expendable and Reusable Forces



information to prepare each day's loadout. In short, we have made unrealistically optimistic assumptions about a mixed fleet and still found no significant cost savings from maintaining two fleets.

In conclusion, if attrition is assessed to average 65 percent or more throughout an extended conflict, the reusable platform is not favored. In such scenarios, the overall U.S. campaign plan may not be executable, although that is beyond the scope of this analysis.

However, if attrition can be projected to eventually decrease to below the 65 percent threshold, the reusable system provides the capability to conduct cost-effective operations for an extended period of time. If the decision is made to procure a reusable system, there is no point in supplementing it with a different expendable system for the first few days or even weeks of high attrition.

Consideration of Program Lifetime

The previous analysis assumed that any program for expendable or reusable vehicles would have a lifetime of 30 years. Our costs were based on that assumption. However, this assumption may not hold in the real world. Technology may evolve, making it desirable to replace systems designed with, for instance, 2020 technology with more cost-effective technology available in 2030. This could result in modifications or replacement of older hardware. Because an important purpose of the systems under discussion is defeating threat systems, which are themselves evolving, it is quite possible that system changes will be required to maintain effectiveness in a changing environment.

In this section, we examine the different effects of system replacement after ten years versus after 30 years for both expendable and reusable technology. Figure 9 shows a nominal spending profile for our breakeven point, a case in which the United States prepares for only five days of combat. This may not constitute a sound plan, but it is the case in our baseline scenario, in which the total procurement and sustainment costs for the expendable and reusable options over 30 years for the program are the same. The key point is that the largest amount of spending for expendable systems is the upfront procurement for the initial quantity plus the replacement quantity purchase of all the flight articles needed over the 30-year time frame. We spread that upfront procurement spending over the first five years. For the reusable system, about one-half of the total cost over the same 30 years is for the sustainment of the reusable UAVs and training of the personnel operating the recovery systems. This cost is incurred every year that the reusable UAV system is owned. The upshot is

FIGURE 9

Spending by Year for Expendable and Reusable Systems

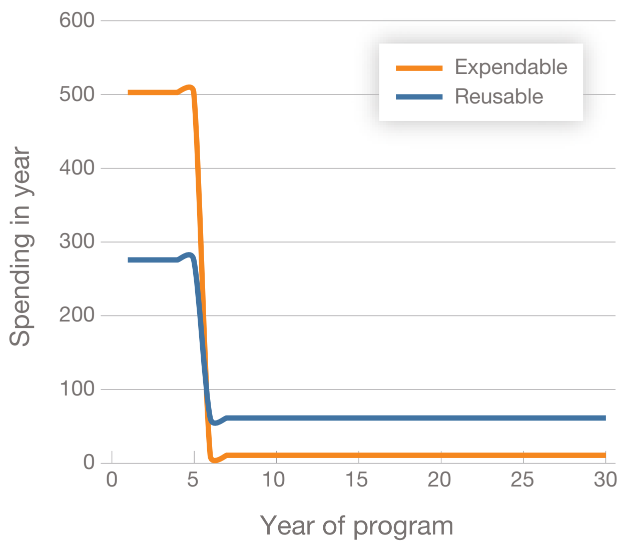
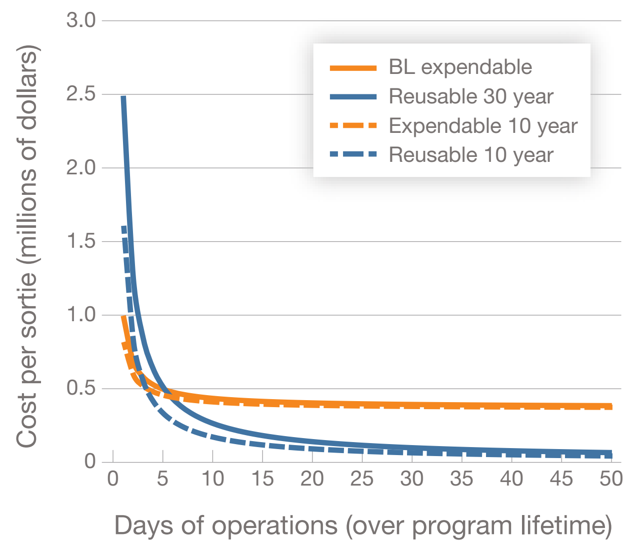


FIGURE 10

Comparison of Systems with Ten and 30-Year Lifetimes



that, for the same level of total spending, the year-by-year allocation is different. The spending in the expendable case is heavily front-loaded.

Figure 10 shows the comparison of the cost per sortie for systems that have only a ten-year lifetime with the cost per sortie of identical systems with a 30-year lifetime.

The ten-year system costs are naturally lower, because the cost of 20 years of operations more than ten years in the future is omitted for the ten-year case. The interesting point is that the reusable costs are substantially lower in cases of only a few days of use, while the expendable system costs are only slightly reduced. This is the result of recovery-unit sustainment cost being spread over the system lifetime. Note the way we estimated the cost: even one sortie of the reusable system requires a full lifetime of recovery-unit sustainment. After all, there is no way to know in advance the year in which the one sortie may be required.

The model in Figure 10 quantifies an obvious and correct intuition. It is easier to upgrade or replace a few articles designed to be reused than a large number of articles stockpiled to support a campaign of expendables.

Conclusions

This report starts with a simple comparison of expendable and reusable platforms. We then present a wide range of excursions about our initial assumptions. The overall trend is clear. Except in the case in which we procure and employ a dedicated C-130 to perform airborne recovery, a case that turns out to be very expensive, the reusable is always favored by a substantial margin if the conflict requires more than a few sorties. The expendable platform is only a desirable solution if the Department of Defense can be certain that the system will not be used more than a few times over its lifetime, attrition will remain high for long periods of time, or if recovery costs will be quite high.

Our analysis looked at platforms of a few hundred pounds that have the speed to keep up with a penetrating package. Such platforms, similar to DARPA's Gremlin program, could be used as decoys; electronic attack platforms; intelligence, surveillance, and reconnaissance platforms; or even weapons carriers. It is possible that such platforms could be useful throughout an air campaign. Even after air superiority is achieved, maintaining the lowest possible level of attrition is an important objective. Reusable UAV technology makes such support assets cost-effective for employment in an extended campaign.

Appendix. List of Assumptions for Baseline Case

Cost

Cost of expendable article	$364,000
Cost of reusable article	$496,600

Refurbishment and Attrition

Refurbishment	1 percent of vehicle procurement
Attrition	1 percent per sortie

Reusable Sortie Rate

Reusable sortie rate	0.5

Ground Recovery

Recovery rate	4 vehicles per unit per day
Unit definition	2 enlisted personnel, 1 vehicle (truck)
Personnel cost	$50,000/year for 30 years
Vehicle cost	$50,000

For 200 sorties per day, this is equivalent to

- 100 recovery crew
- 50 recovery vehicles
- $993,200 per day in spare parts consumption (based on 1 percent refurbishment assumption)
- $2,000,000 in dedicated equipment.

Training

- 10 training missions per year per sortie per day capability.
- For the expendable case, one reusable training article purchased for each sortie per day capability.
- If training for the use of expendable vehicles required actual consumption of expendable units, costs of realistic training would be prohibitive. So we assume that a reusable training vehicle is used to simulate operations with expendable systems. We also assume the training establishment is sized to reflect the size of planned wartime missions. If the U.S. Air Force plans to operate, for instance, ten vehicles at the same time, it needs to train with ten vehicles at the same time.
- Training attrition and refurbishment cost 0.1 percent per sortie.
- Training recovery costs $500 per recovery (peacetime training recovery does not require prompt recovery or dedicated assets; therefore, it is charged at marginal costs).

Training is included in this list based on the assumption that the vehicle will be used in conjunction with other assets, particularly manned aircraft. Small air vehicle operations are necessary to provide a realistic training environment for larger aircraft operating in the same airspace. The air vehicles themselves are highly automated and may require little actual flying time to keep launch and recovery crews mission-capable.

Note that the training requirements are broadly similar for both expendable and reusable vehicle concepts. Therefore, the training assumptions do not have much impact on the trade between expendable and reusable concepts of operations.

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About This Report

This report is a summary of analysis conducted by RAND Corporation researchers of the comparative cost-effectiveness of reusable and expendable platforms for small unmanned aerial vehicles (UAVs). Our analysis looks specifically at costs to achieve a fixed effectiveness. In particular, it examines the life-cycle costs of alternative small UAVs that would operate in defended airspace in support of other systems, such as strike aircraft, and either be expended after their mission or recovered via aircraft or on the ground. Our baseline systems operate at high subsonic speeds and carry a modest mission payload of around 60 pounds. This work should be interest to national security planners considering options for future air warfare systems.

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