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One Engine Inoperative (OEI) and Autorotation for Heavy Lift Rotorcraft System

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NOMENCLATURE

AEI	All engines inoperative
FAA	Federal Aviation Administration
FADEC	full authority digital engine control
HOGE	hovering out-of-ground-effect
LDP	landing decision point
MCP	allowable aircraft maximum continuous power operation
OEI	one engine inoperative
rpm	revolutions per minute
TDP	takeoff decision point
V_y	velocity for best climb speed
V_{toss}	velocity for takeoff safety speed

ONE ENGINE INOPERATIVE (OEI) AND AUTOROTATION FOR HEAVY LIFT ROTORCRAFT SYSTEM

Tom Wood[1]

Ames Research Center

The Federal Aviation Administration (FAA) will certainly require the Heavy Lift Rotorcraft to be operated under Category A performance and operations requirements. Because of the weight, no operation will be allowed except Category A according to FAA Part 29.1(c). This means that anywhere along the flight path, the aircraft must be able to either land safely following an engine failure or continue flight. A repeatable flight profile must be developed and executed to ensure that the aircraft can be safely landed, or flown away, depending on its location on the flight profile. This means that there will be no Height-Velocity testing as is currently required for Part 29 Category B. Because all the configurations shown to date are different than existing rotorcraft, each type would have to develop their individual requirements under existing special conditions, FAA Part 21.17(b). This means the FAA will take the opportunity to negotiate additional requirements or change requirements to ensure safety. For example, because the tiltrotor did not fit normal rotorcraft category, new rules were negotiated between the applicant and the FAA. As a result of this negotiation, performance requirements for Category A were increased. The rules were written in terms of guaranteed performance instead of Category A requirements. Detailed discussion will follow later. The proposed tiltrotor would likely follow along with the current tiltrotor rules with the possibility of increased Category A performance requirements. Compounding with the addition of wing and auxiliary thrust to both the tandem and coaxial rotor would result in new special condition aircraft. To my knowledge, no compound tandem or compound coaxial rotor has ever been certified by the FAA.

Recent experience in certification of rotorcraft for Category A performance (M430, M412, and M427), along with analysis conducted during the design of the first commercial tiltrotor (BA609), has provided some parametrics that can be used to estimate the Category A performance capability. Many factors can influence these data, but they do represent demonstrated performance. Parametrics for the BA609 were developed using man-in-the-loop simulation. NASA also conducted considerable simulation efforts along these lines over the past several years. The ground-level helipad in confined areas turned out to be the most difficult even though the elevated helipad is very demanding due to the surrounding environment. The primary difference is in the height of the takeoff decision point (TDP). The elevated helipad can use drop-down height below the helipad while ground-level cannot. Examples of the ground-level helipad flight profiles are shown in figures 1–4. Normal vertical takeoff is shown in figure 1. Here the pilot moves the aircraft up and back using a slow rate of climb while maintaining the helipad in his window. This is referred to as the site picture. Once the TDP is reached, the pilot accelerates the aircraft to velocity for takeoff safety speed (V_{toss}) and initiates a climb. At 200 feet above the takeoff surface the pilot accelerates to

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velocity for best climb speed (V_y) where he climbs until he is 1,000 feet above the takeoff surface. Normal vertical landing flight profile is presented in figure 2. The pilot enters the approach window at 200 feet and 30 KIAS while decelerating to the landing decision point (LDP) where he acquires the correct site picture out his window. The one engine inoperative (OEI) flight profiles for rejected takeoff and balked landing are shown in figure 3. Rejected takeoff can occur anywhere between liftoff and the TDP. If power is lost along this flight profile, the pilot must be able to safely land the aircraft back on the helipad. For this approach, the TDP and LDP are the same values. If power failure occurs at LDP, the pilot must be able to fly away and clear the helipad by 15 feet while accelerating to V_{toss}. The OEI completed landing flight profile is shown in figure 4. If power failure occurs at LDP or later, the pilot can continue the landing to the helipad safely. These flight profiles were developed to allow very little, if any, sliding on the helipad following an OEI rejected takeoff or OEI completed landing. This approach is considered to be the limiting Category A case and, therefore, would become a criteria for use in this conceptual design study. It should be noted that these flight profiles must be flown on each takeoff and landing to helipad to ensure safe takeoffs and landings.

The flight data and simulation data were reviewed to develop simplified criteria for use in conceptual studies. Category A analysis is generally broken into three segments. The segments are takeoff and landing, climb at velocity for takeoff safety speed (V_{toss}), and climb at best climb speed (V_y). A weight is established for the requirements of each segment at given atmospheric condition and appropriate power setting, and then the minimum weight of the three segments becomes the limiting weight. The limiting segment for helipad was the landing and takeoff phase for the majority of the atmospheric conditions. The data is presented as power ratio versus disk loading as shown in figure 5. Power ratio is defined as the OEI power available at the given atmospheric condition divided by the hovering out-of-ground-effect (HOGE) power required at the weight for the given atmospheric conditions. The OEI power available may be either 30-second or 2.5-minute power. From figure 5, the demonstrated performance is in the area of 6–7 pounds per square foot of disk loading. Simulation results are presented at 15 pounds per square foot. A linear curve is suggested as shown. Scatter exists in the measured data that suggests there are other factors involved. However, as an initial criterion, the power ratio appears to be a reasonable approach. For configurations with more than two engines, the power ratio would be the sum of the remaining engines' OEI power divided by HOGE power required. For this study, a power ratio of 0.9 is recommended to account for the uncertainty resulting from lack of demonstrated helipad data for tiltrotors.

The one engine inoperative rating structure varies according to the manufacturer and the time frame that the engine was certified. The addition of Full Authority Digital Engine Control (FADEC) has allowed an improved OEI rating structure such as 30-second OEI power. Engines that Bell has certified in aircraft that have Category A performance are summarized in figure 6. The engine rating structure is presented in terms of a ratio of OEI power to allowable aircraft maximum continuous power operation (MCP). This is in keeping with the NASA study, which uses OEI as a percent of MCP. For engines with a 30-second OEI rating, the power ratio varies between 1.3 to 1.4 times MCP. A 2-minute or 2.5-minute OEI varies between 1.25 to 1.35 times MCP. A 31-minute OEI varies between 1.2 to 1.3 times MCP. It is recommend that engine manufacturers provide a 30-second OEI rating structure to minimize impact on sizing of MCP for this study.

As mentioned earlier, the FAA will negotiate different requirements for Special Condition certification as opposed to Part 29 rotorcraft. A comparison between helicopter and tiltrotor Category A requirements is shown in table 1. For tiltrotors, the takeoff path extends to 1500 feet. Rate-of-climb requirements at V_{toss} and V_y are increased. Also, an enroute OEI paragraph was added to provide the pilot with single-engine climb or descent gradients. For example, if the criteria for this study is takeoff at maximum gross weight at 5000 feet on ISA +20 deg C day, then one must consider the ability of the aircraft to stay up in the event an engine failure occurs in cruise. Because these atmospheric conditions could represent Denver in the summer, stay-up capability OEI in the order of 12,000 feet would be desirable to miss the mountains by at least 1,000 feet.

The question of autorotation in the nonconventional rotorcraft that are being considered in this study needs to be discussed. The FAA requires a full auto touchdown from cruise for all Part 29 helicopters according to FAA Part 29.79(b). The addition of the wing for all configurations along with high speed complicates the issue and requires special attention to evaluate. The FAA has taken the position to date that autorotation must be demonstrated in tiltrotors. This demonstration requires a full auto touchdown at maximum gross weight at sea level standard from a straight-in approach, which is the same requirement for helicopters (TR.79 (b)). The use of a large wing on all the configurations complicates the control of the rotor rpm during descent due to the load sharing between the rotor and the wing. The rate of descent that must be overcome in all engine inoperative (AEI) is a function of disk loading as shown in figure 7. Here a clear trend can be observed between the measured sink rate for autorotation and disk loading. For configurations that use four engines, the position that full auto touchdown should not have to be demonstrated should be negotiated with the FAA. It should be debated that a demonstration of flare effectiveness AEI followed by power recovery would be adequate. However, AEI controllability should have to be demonstrated. Autorotation was investigated using the XV-15. Figure 7 shows the value of the sink rate required for autorotation for the XV-15. In airplane mode, the proprotors can windmill. Results of windmilling of the proprotors for the XV-15 are shown in figure 8. However, the proprotors could not be stopped from turning in order to drive the generators on the transmission. An AEI reconversion was flown as shown in figure 9. Finally an autorotative flare was flown to demonstrate that the autorotative sink rate could be arrested as presented in figure 10.

In summary, a power ratio (OEI power/HOGE power) of 0.9 is recommended for this study to provide ground-level-helipad Category A performance. It is recommend that the engine manufacturers provide an engine rating structure that provides 30-second OEI power. Attention should be paid to the OEI power requirements because this aircraft will only be allowed to operate Category A. Recognize that the FAA will negotiate higher Category A requirements than are currently in Part 29 during development of special condition rules. An attempt should be made to negotiate with FAA to demonstrate flare effectiveness followed by power recovery instead of a full auto touchdown.

TABLE 1. COMPARISON OF CATEGORY A PERFORMANCE REQUIREMENT BETWEEN HELICOPTER AND TILTROTOR

Description	Part 29	Helicopter	Part TR	Tiltrotor
Takeoff Path	29.59	1000 ft	TR.59	1500 ft
V_{TOSS} Altitude	29.59(b)	200 ft	TR.59 (b)	400 ft
V_Y Altitude	29.59(c)	1000 ft	TR.59(c)	1500 ft
OEI Climb at V_{TOSS}	29.67(b)	100 fpm	TR.67 (b)	200 fpm
OEI Climb at V_Y	29.67(c)	150 fpm	TR.67(c)	1.20%
Enroute Flight Paths	n/a	n/a	TR.69 (b)	Show gradient

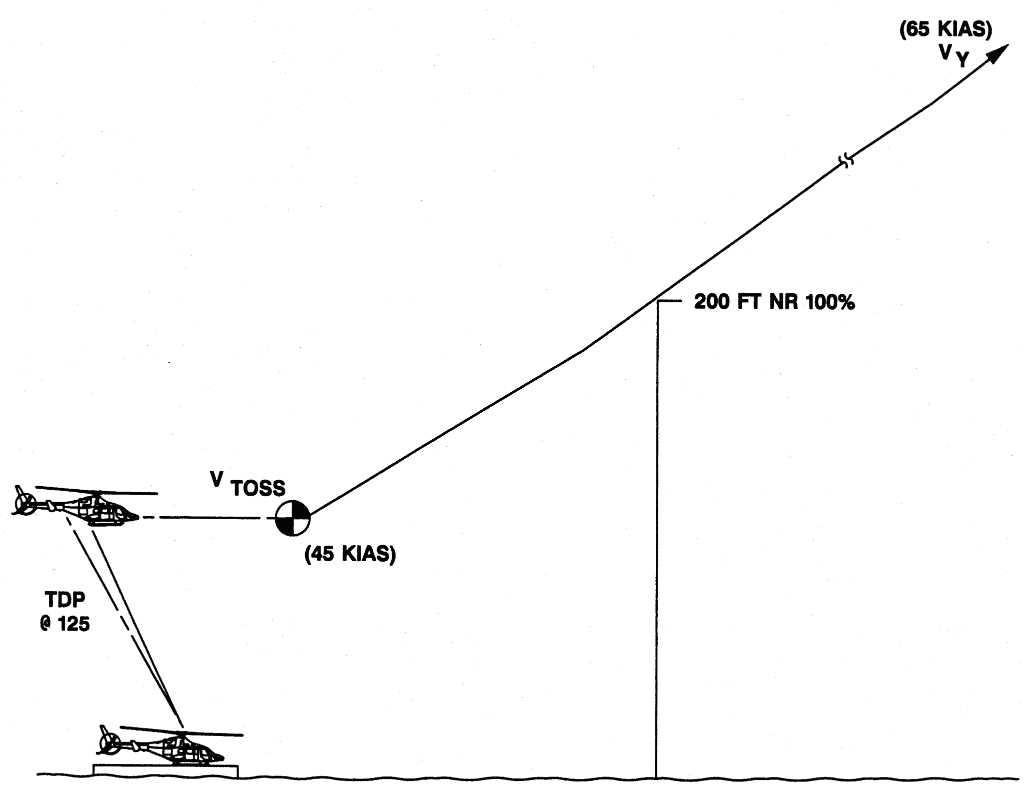

Figure 1. Normal vertical takeoff.

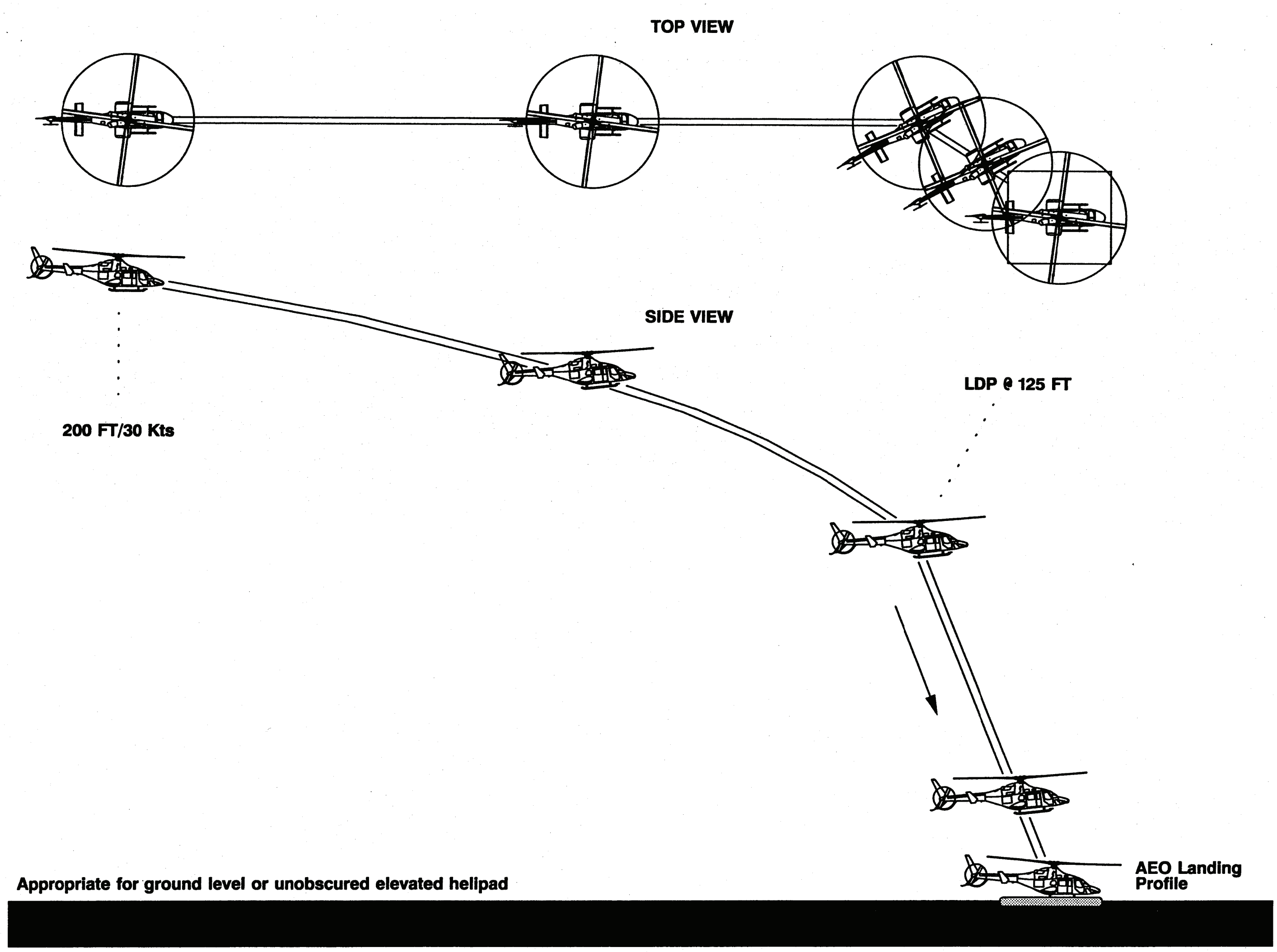

Figure 2. Normal vertical landing.

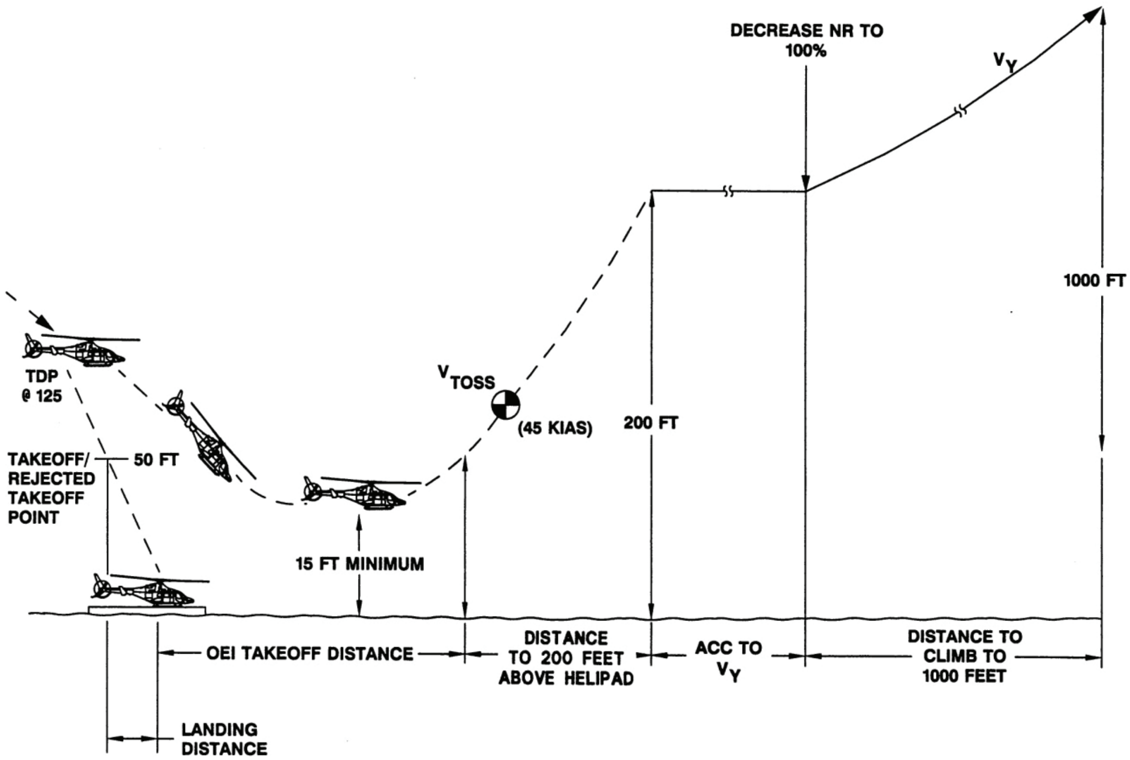

Figure 3. OEI completed rejected takeoff/balked landing profiles for helipad.

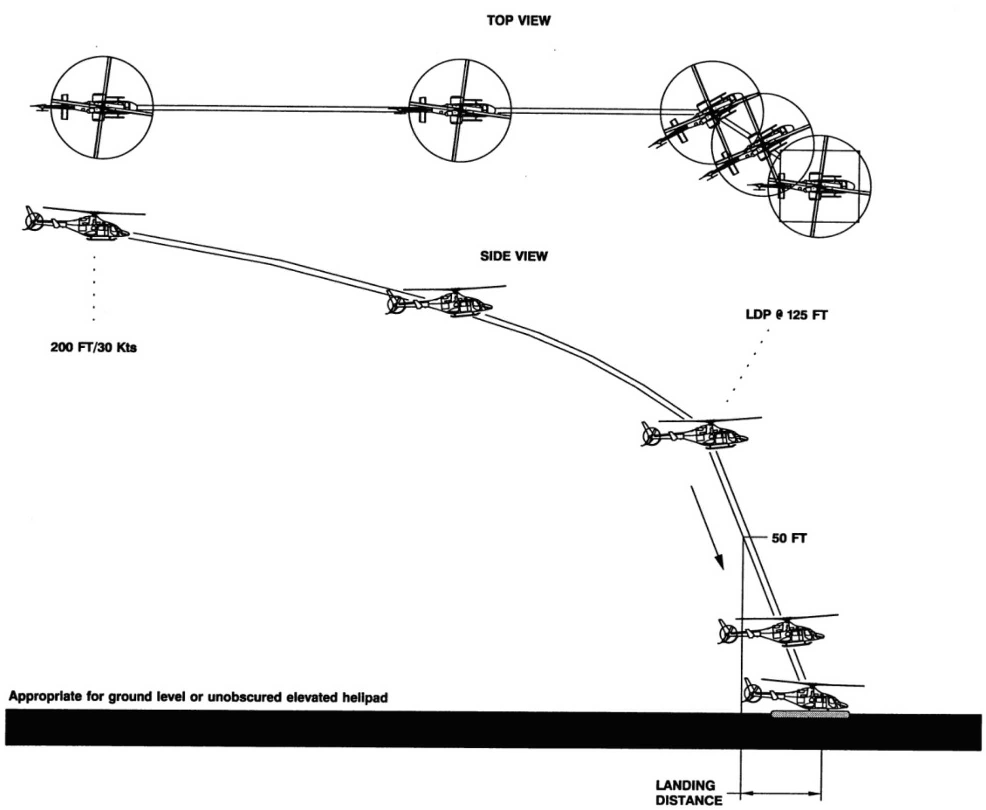

Figure 4. OEI completed landing profile for helipad.

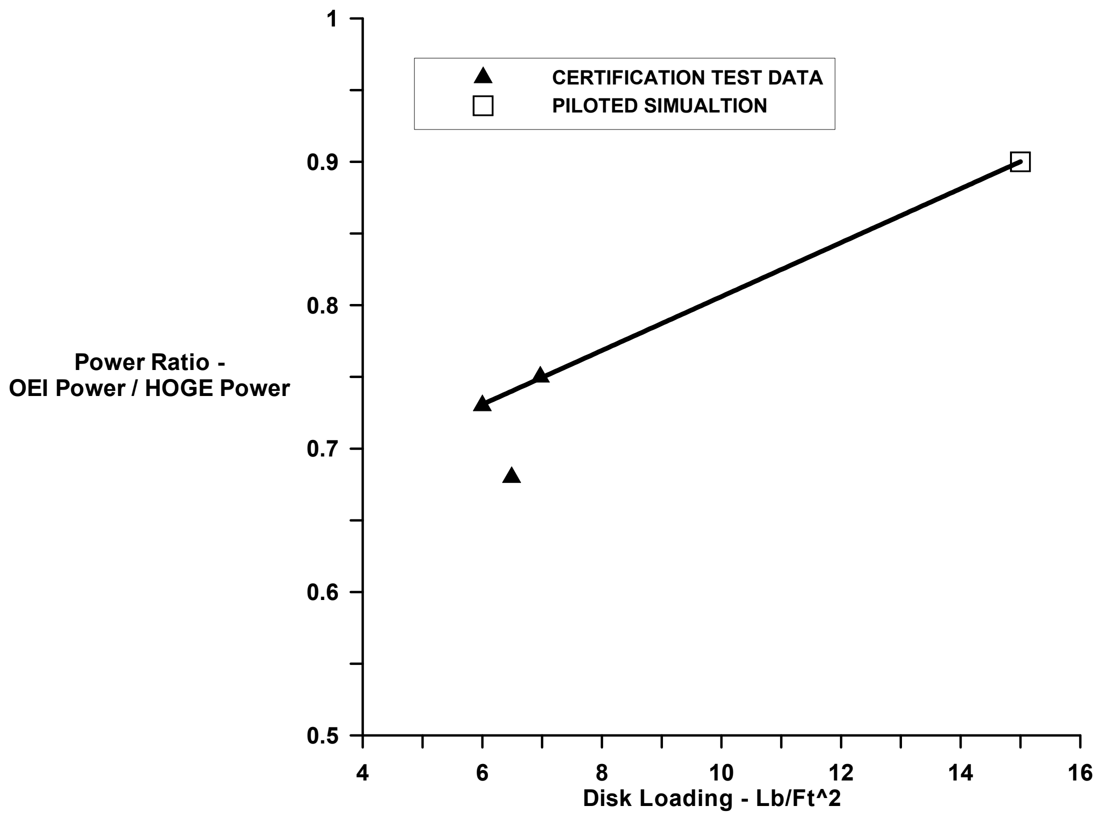

Figure 5. Demonstrated values of power ratio to achieve vertical helipad performance.

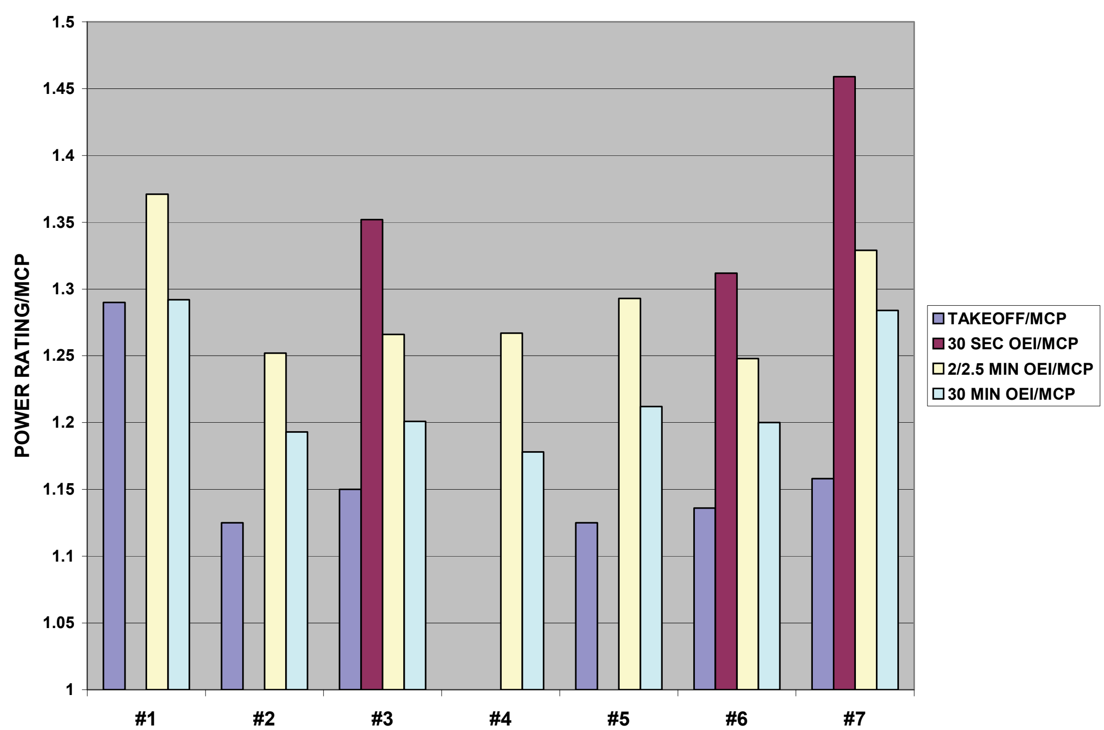

Figure 6. Current engine rating structure for OEI operation.

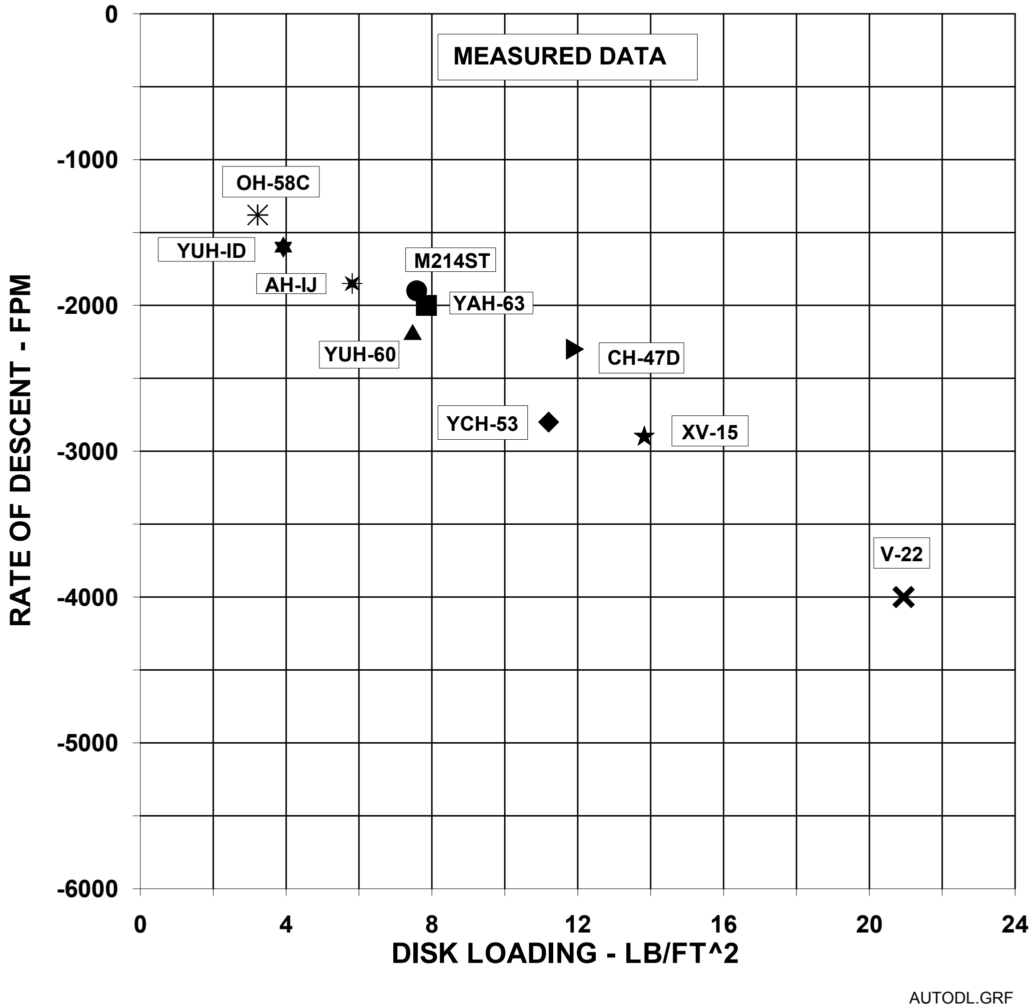

Figure 7. Autorotation sink rate as a function of disk loading.

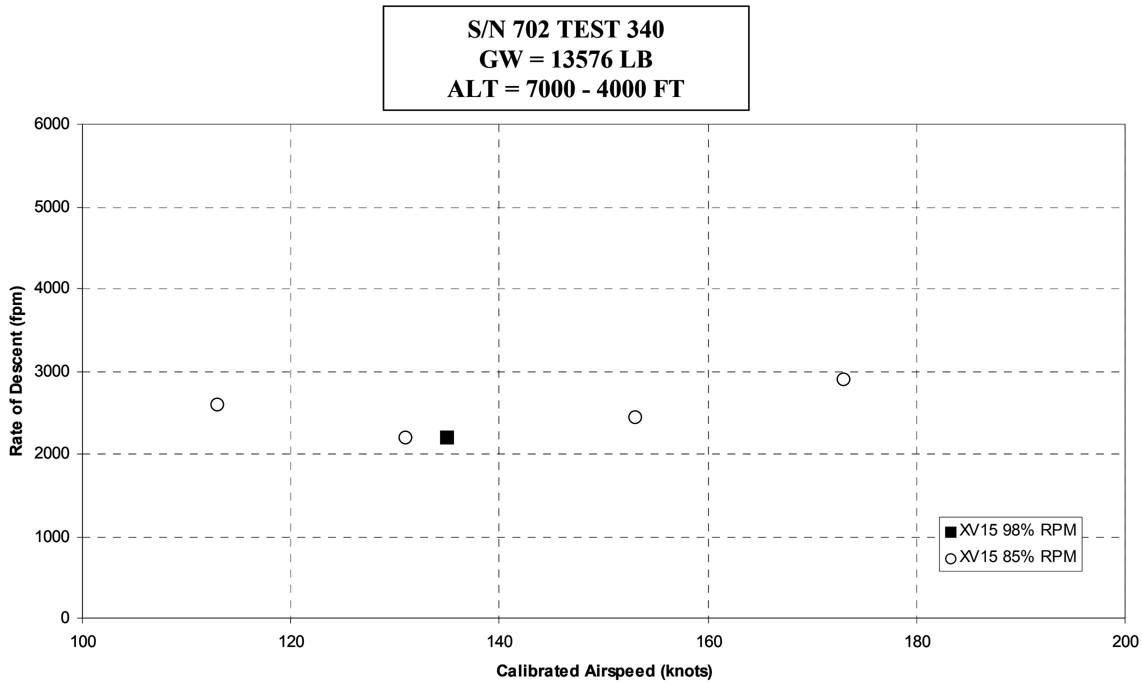

Figure 8. XV-15 demonstrated windmilling.

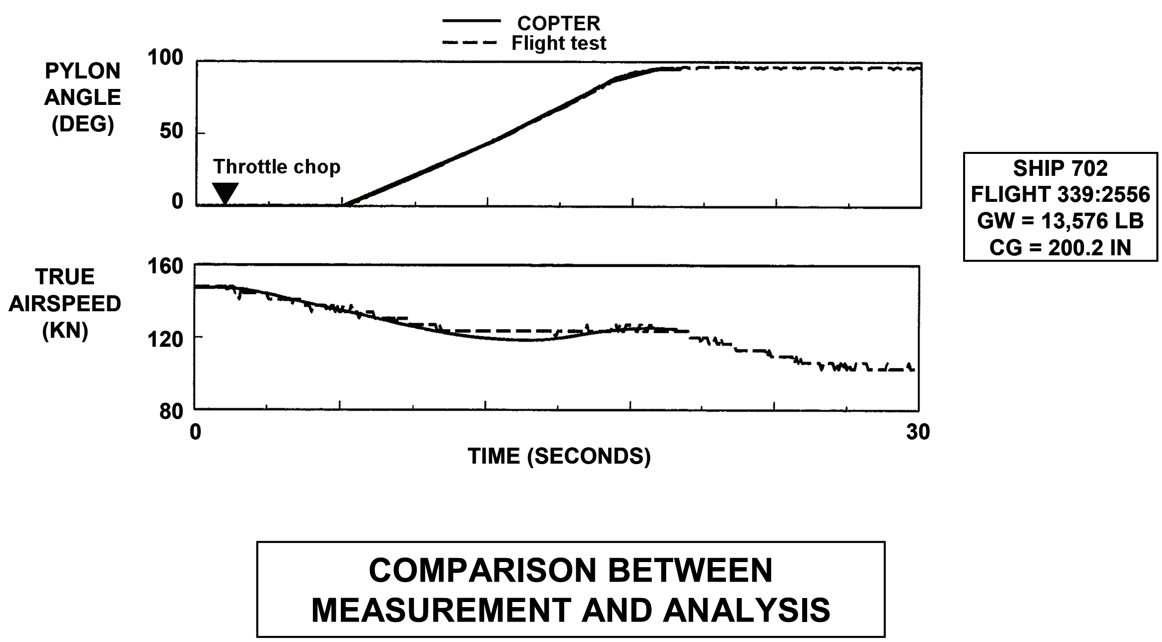

Figure 9. XV-15 AEI reconversion.

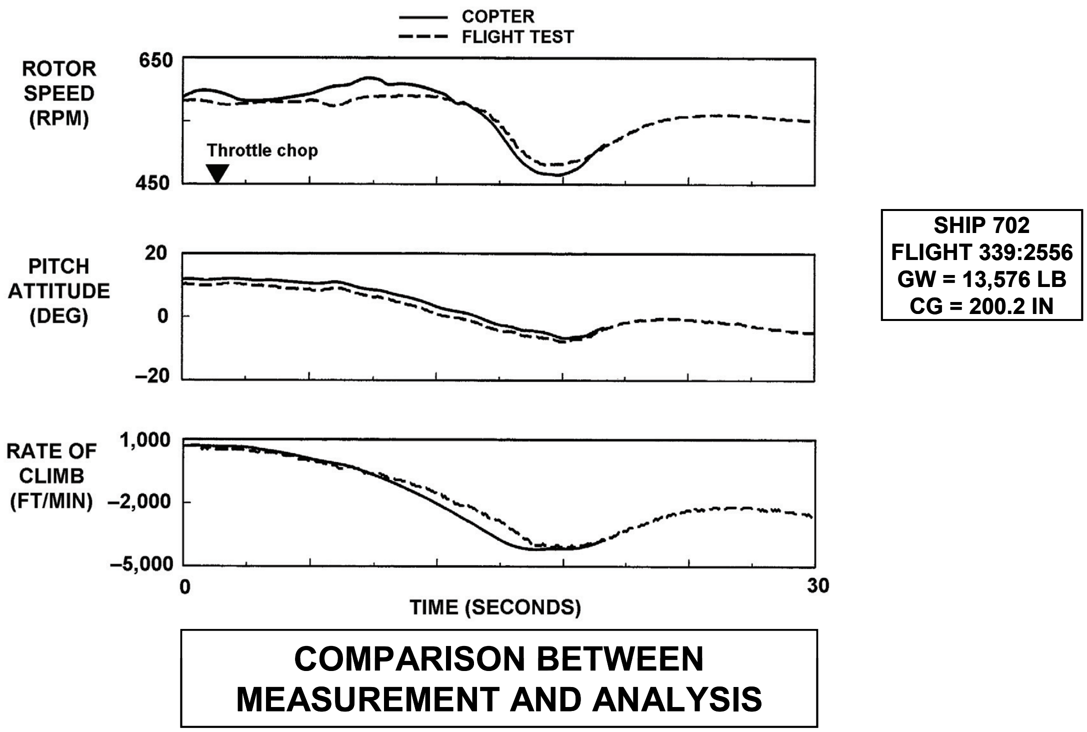

Figure 9. (cont.)

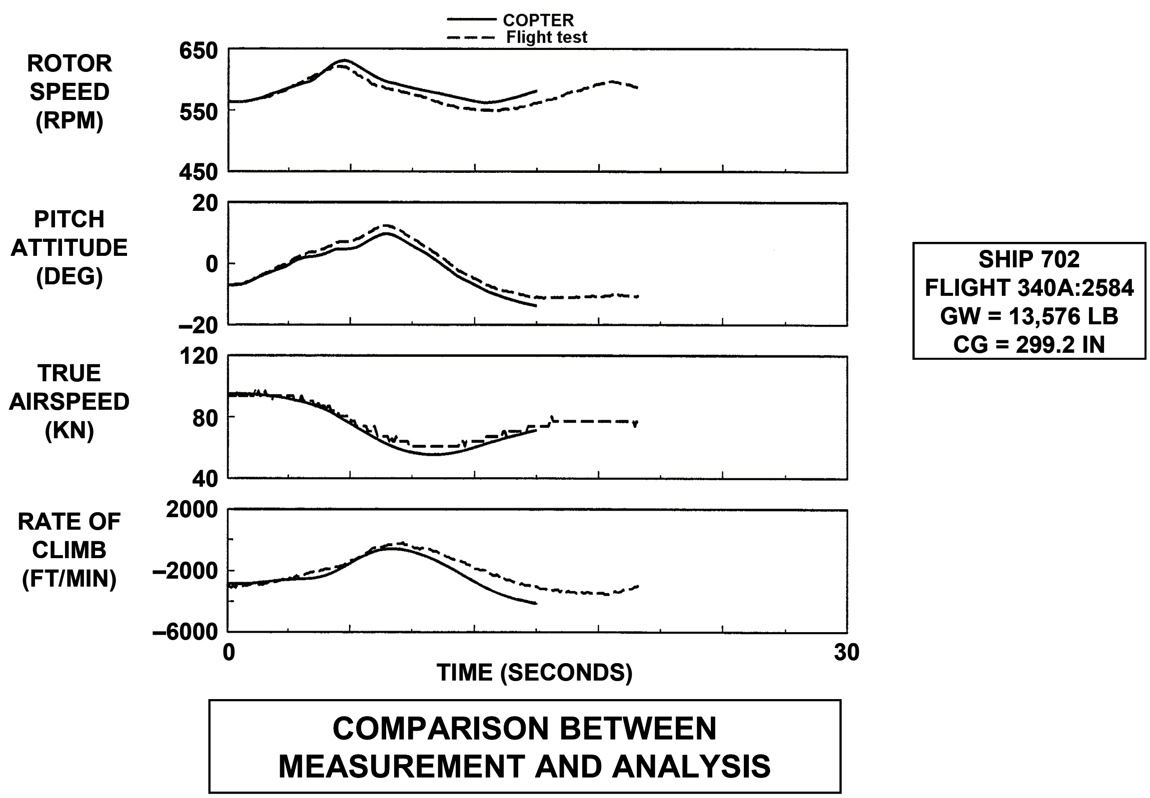

Figure 10. XV-15 AEI flare effectiveness.