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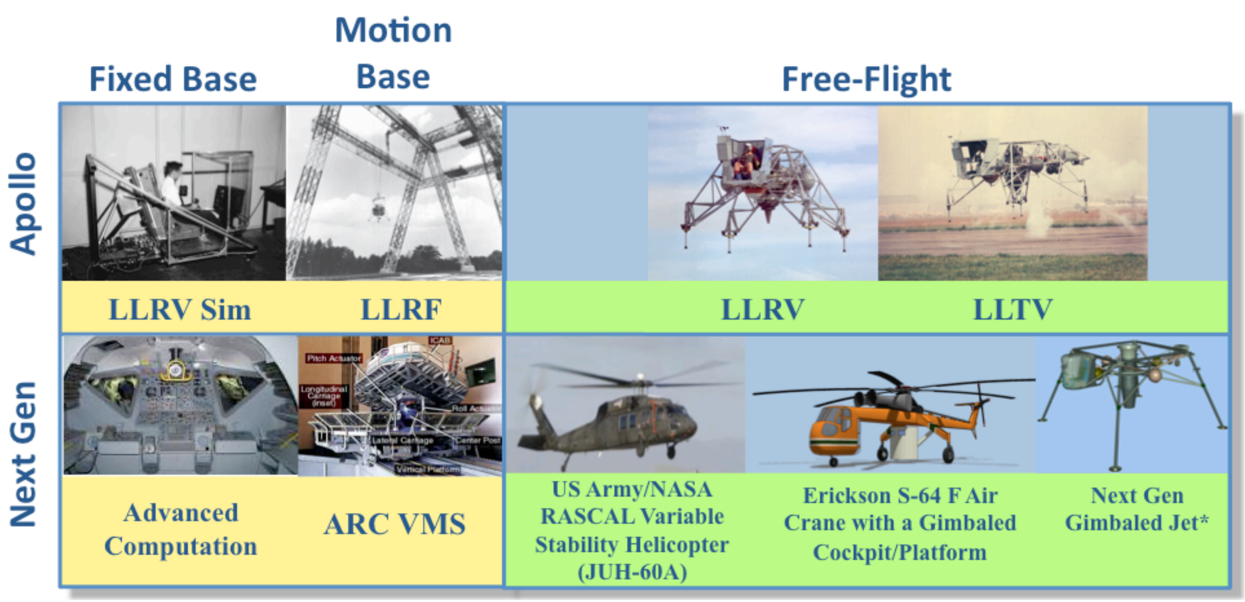
A Toolset for an Advanced Landing Technology Development and Training Program

Fixed Base, Motion Based, and Three Free-Flight Terrestrial Variable-*g* Landing Research Vehicles (V*g*LRVs) to Support Advanced Technology Development for Robotic & Human Spacecraft Landings Beyond LEO

Volume I

May 12, 2010



"Ensuring the Continuation of Excellence for NASA's Human & Robotic Space Missions"

The Continuum of Simulation Technologies

Intelligently Apply Lessons Learned to Meet the New Challenges

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Executive Summary

When developing a human spacecraft landing system there are two missions to consider, first the spacecraft development support to be followed by the development of a training system, which in turn reflects the real needs of the spacecraft. The vehicle concepts presented in this paper are germane to any destination beyond LEO where landings are intended to be made and can support both the spacecraft development and the training mission. These concepts will all be used to simulate various gravity environments and all the candidate vehicles must be capable of this. Taking all of this into consideration, the final vehicle concept should really be considered a "variable *g* simulator" or variable *g* research vehicle (V*g*LRV).

This paper combines a go-forward proposal for human and robotic spaceflight landing systems technology development with the final report for the Constellation Program Lunar Lander Project Office at (LLPO) sponsored trade study for free-flight training systems started in May 2008 by NASA DFRC. This paper has direct applicability to landing systems development for unmanned spacecraft.

The Augustine report emphasized the need for a near-term landing technology development program, which "needs to be started soon" and "will require many iterations". A proposal is presented in this paper for NASA DFRC to lead a feasibility study partnering with several NASA centers and other organizations, which will lead to the definition of a full spectrum of research facilities for space technology crosscutting capability demonstrations spanning a continuum of simulators. The proposed facilities encompass the integration of fixed base simulators, moving base simulators, and a complement of two to three free-flight research vehicles capable of supporting landing systems development for both human spaceflight and unmanned missions.

The goal of the study is to define a continuum of simulations with definitive technical detail as well as cost and schedule information for a comprehensive approach for component and system closed loop flight tests. This landing system development program will leverage the work of Autonomous Landing and Hazard Avoidance Technology (ALHAT) program and Altair landing systems development, applying these to the new NASA technology development mission. This program will also provide NASA with a high visibility, high payoff flight test program that advances spacecraft landing technology development over the near-term as recommended in the Augustine Commission report and lays the groundwork for the training systems. Throughout the history of aerospace development programs, it is widely acknowledged that early flight research effectively enhances paper studies and avoids unnecessary program development costs by teaching real world conditions not possibly identified in extensive paper studies. DFRC believes a spacecraft landing flight research and flight test program should be an essential part of the new technology development program. Starting now will help preserve the critical technologies including Apollo, and the work to date accomplished in the Constellation and ALHAT programs.

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1. Introduction and Background

When developing a human spacecraft landing system there are two missions to consider, first the spacecraft development support, followed by the development of a training system, which reflects the real needs of the spacecraft. The Constellation Program Lunar Lander Project Office (LLPO) commissioned DFRC to look at vehicle concepts for the lunar training mission. The Apollo Lunar Landing Research Vehicle (LLRV) and its development support for the LM preceded the development of the Lunar Landing Training Vehicle (LLTV). Furthermore, there is an impetus in the Augustine report for a landing technology development program as described below:

> "The entry, descent and landing of cargo on Mars is difficult because Mars has sufficient atmosphere to drive the design of landing systems, but inadequate atmosphere for feasible parachutes or wings to safely land astronauts on the surface. Scientific probes landing on Mars have used a complex mix of aerodynamic braking and rocket propulsion. These techniques will have to be improved before larger robotic or crewed missions can be sent to Mars. *This research and technology development program needs to be started soon, because it will require many iterations and increasingly larger missions before NASA is ready to demonstrate a safe, crewed Mars landing. Meanwhile, the intermediate results would greatly benefit future robotic missions.*" [1][Emphasis added]

This is a go-forward proposal for advanced technology development for spacecraft landing systems as well as the final report to summarize the work performed by NASA-Dryden on the Lunar Lander Training Vehicle Trade Study task commissioned by the LLPO on May 15, 2008. Although the Constellation program has been tentatively cancelled and the new destination for human spacecraft landings is unclear, the vehicle concepts in this study are germane to destinations other than the moon. The vehicles described in this study constitute variable *g* free-flight vehicles capable of supporting both spacecraft development and the training mission.

1.1. Task (Trade Study)

On March 5, 2008, at the Go for Lunar Landing Conference (Appendix I) in Tempe, Arizona, NASA Dryden Flight Research Center was asked by the Lunar Lander Project Office (LLPO) to submit a proposal to investigate the use of free-flying vehicles to perform the lunar landing flight training task. A proposal was developed and sent to the LLPO on March 20, 2008. The task was officially kicked-off at Dryden on May 15, 2008.

1.2. Team Composition

A team of Dryden employees and outside consultants was assembled to perform the work in this task. The following individuals have made significant contributions to the work represented in this report.

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[1] Page 102 of the Augustine Commission Final Report, "SEEKING A HUMAN SPACEFLIGHT PROGRAM WORTHY OF A GREAT NATION"—Section 7.4, MARS ORBIT TO SURFACE TRANSPORTATION

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1.3. Acknowledgements

Special thanks are in order for others who have made significant contributions to this work. Special thanks go to the Honorable Dr. Harrison Schmitt, Apollo 17 Lunar Module (LM) pilot, for his efforts to facilitate communication with the Apollo astronaut corps. On December 9, 2008, the LLPO hosted an expert panel review, which provided many answers to questions raised in the initial trade study phase. The Apollo participants included three commanders from Apollo 11, 16, and 17 (Armstrong, Young, and Cernan) plus the Apollo 17 LM Pilot Schmitt. Wayne Ottinger represented the Apollo LLRV and LLTV projects and Charles "Scorch" Hobaugh and James "Mash" Dutton, Jr. represented the astronaut crew office. Though unable to be present, Dave Scott performed a much appreciated detailed analysis and commentary on the conference transcripts[1] included in this paper. Also, Joe Tanner, former Shuttle Training Aircraft Instructor Pilot and Mission Specialist, contributed helpful insights from the Space Shuttle training program. Finally, thanks to the fine people at Orbital Sciences Corporation, Chandler, Arizona and Erickson Air-Crane, Inc., Medford, Oregon for their significant contributions to the concepts in this paper.

Dr. Chuck Oman, MIT Man-Machine Interface Laboratory, responded to questions in Appendix B on the human factors involved and his inputs are valued in this study.

CDR Robert Byers, USN, Team Member / Consultant, Rotary Wing Instructor Pilot, U.S. Naval Test Pilot School authored an independent paper to the SETP Flight Test Safety Committee, May 2008, Appendix F, and was instrumental in providing current technology for variable stability helicopter contributions to this study. He also evaluated the S-64 F Air Crane on a test flight and the flight report is in Appendix E.

C. Wayne Ottinger, Team Member, SAGES consultant authored a white paper, Appendix G, which contributed significantly to this report.

[1] A companion three-DVD set is available that describes the key technical discussions covering 40 video clips for 87 minutes. Selected quotes from these clips are used in the following discussions.

2. The Proposal

*2.1. A Variable g Landing Research Vehicle (*V*g*LRV*)*

The vehicle concepts presented here are germane to destinations beyond LEO and can support both the spacecraft development and the training mission. Since all of the concepts have thrust-to-weight equal to or greater than 1, they can all potentially simulate the range of gravities 0 through 1 *g*. However, the fidelity of that simulation will vary from concept to concept, as discussed in this report. Taking all of this into consideration, the final vehicle concept should really be considered a "variable *g* simulator" or variable *g* research vehicle (V*g*LRV) and can be used for landing system development and training to all destinations currently under consideration by NASA.

An example of landing system development support is performing piloted evaluations of a particular control strategy for these new spacecraft. Certainly, some concepts will accommodate the development and test function better than others. Each concept's ability to accommodate lander system development is discussed in the report.

In Apollo, the Lunar Landing Research Vehicle was conceived and designed before the Lunar Orbit Rendezvous (LOR) approach was established for the lunar landing mission, the LLRV pioneered the techniques and system development needed for both the LM spacecraft design as well as the training of pilots. The JSC Constellation/Altair project office sponsored a trade study for the selection of a free-flight lunar landing trainer, which has led to an early emphasis on training concepts, chiefly a comparison of Space Shuttle training vs. the Apollo training experiences. The following discussions address these differences.

However, it should be recognized that the early flight testing utilizing flight research vehicles needs to precede any trainer development in the future, just as in Apollo, and therefore the anticipated DDT&E requirements for new spacecraft landers should dictate the design and development of flight research vehicles, which will then evolve into trainers. Therefore, the discussion following Section 4, Section 5 and Appendices should be viewed as trainer oriented issues, still useful for consideration, but not exclusively of a new spectrum of flight research vehicles. The three candidate flight vehicles are the Gimbaled Jet, the Air Crane, and the Rascal VSS Helicopter.

2.2. NASA DFRC Study for an Advanced Landing Technology Toolset

NASA DFRC proposes to further develop the feasibility of a flight research program through continued analysis and definition of an integrated utilization of the three selected concepts. This includes building on the work of Orbital Sciences for the Gimbaled Jet, conducting flight tests of the S-64 Air Crane to confirm flight dynamics, and to further define the role of the Rascal VSS Helicopter. Additional partners proposed for this effort include:

- NASA JSC – Altair, ALHAT
- JPL – ALHAT, other EDL systems
- NASA ARC – Vertical Motion Simulator (VMS) & Rascal VSS Helicopter

- NASA LaRC – Lunar Landing Research Facility (LLRF), flight controls
- U. S. Navy Test Pilot School – SH60 Variable Stability Seahawk experience, helicopter flight test expertise
- Army Aeroflightdynamics Directorate – helicopter flight dynamics & Rascal VSS Helicopter
- Draper Laboratory – pilot-vehicle interface & flight controls
- Northrop Grumman Corp. – landing systems research

The goal of the study is to define a continuum of simulations (Figure 1) with definitive technical detail as well as cost and schedule information for a comprehensive approach for component and system closed loop flight tests. This landing system development program will leverage the work of Autonomous Landing and Hazard Avoidance Technology (ALHAT) program and Altair landing systems development, applying these to the new NASA technology development mission.

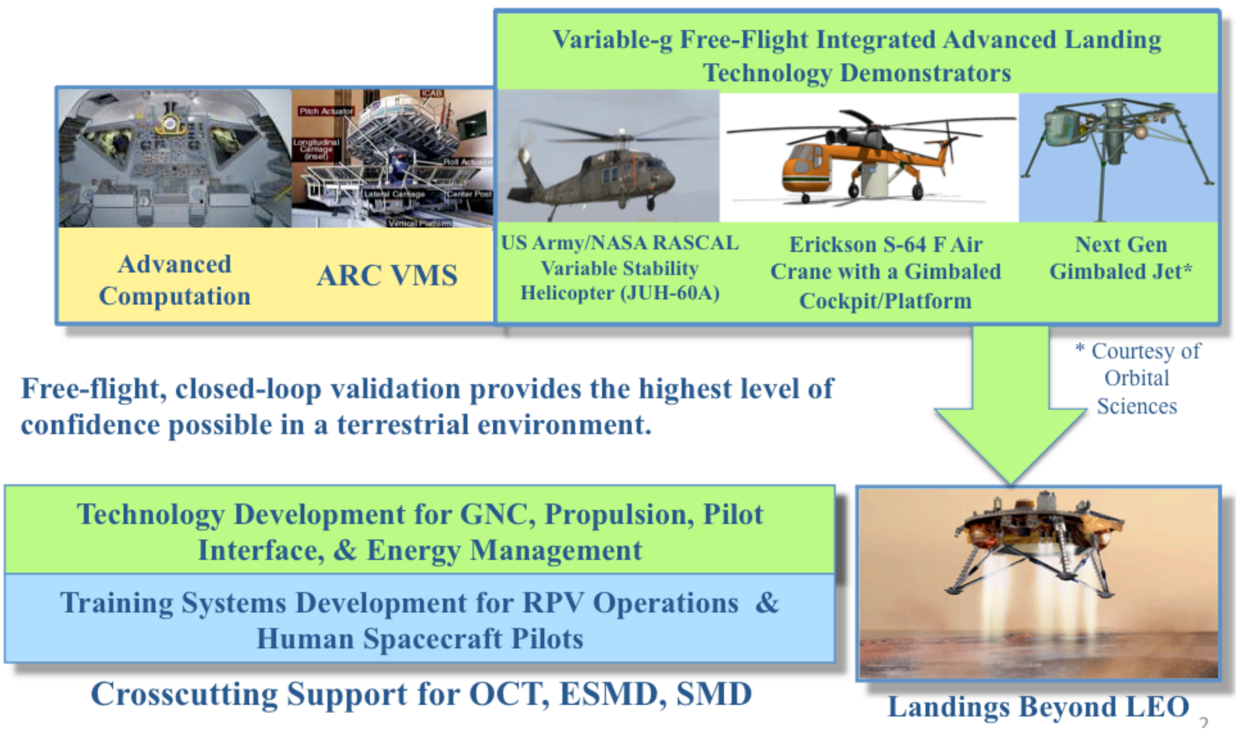

Figure 1 Continuum of Sims

This program will also provide NASA with a high visibility, high payoff flight test program that advances spacecraft landing technology development over the near-term as recommended in the Augustine Commission report and lays the groundwork for the training systems. Throughout the history of aerospace development programs, it is widely acknowledged that early flight research effectively enhances paper studies and avoids unnecessary program development costs by teaching real world conditions not possibly identified in extensive paper studies. DFRC believes a spacecraft landing flight research and flight test program should be an essential part of the new technology development program. Starting now will help preserve the critical technologies including Apollo, and the work to date accomplished in the Constellation and ALHAT programs.

The study will address the entire spectrum of simulations—fixed base, motion base, and free-flight—that make a sound landing technology development program for NASA, supporting long-term spacecraft landing simulators that will support DDT&E of those spacecraft landers. As shown by Apollo and recognized by the Augustine Commission, this type of technology development is a long-term process, goes through many iterations, and will be required for any future manned landings. Starting now will help preserve the critical technologies, including Apollo, and the work to date accomplished in the Constellation and ALHAT programs.

A one-year study (in the $2-4 million range), lead and managed by DFRC and supported by those partners listed above, will lead to a definitive proposal including pertinent flight test results (i.e., Air Crane flight dynamics) for an optimally designed flight research program for long term development of spacecraft landing systems for both humans and autonomous landings for a full range of destinations beyond low earth orbit.

Figure 2 below illustrates the opportunity to intelligently apply the Apollo lessons learned to the technology challenges of the future spacecraft landing system developments.

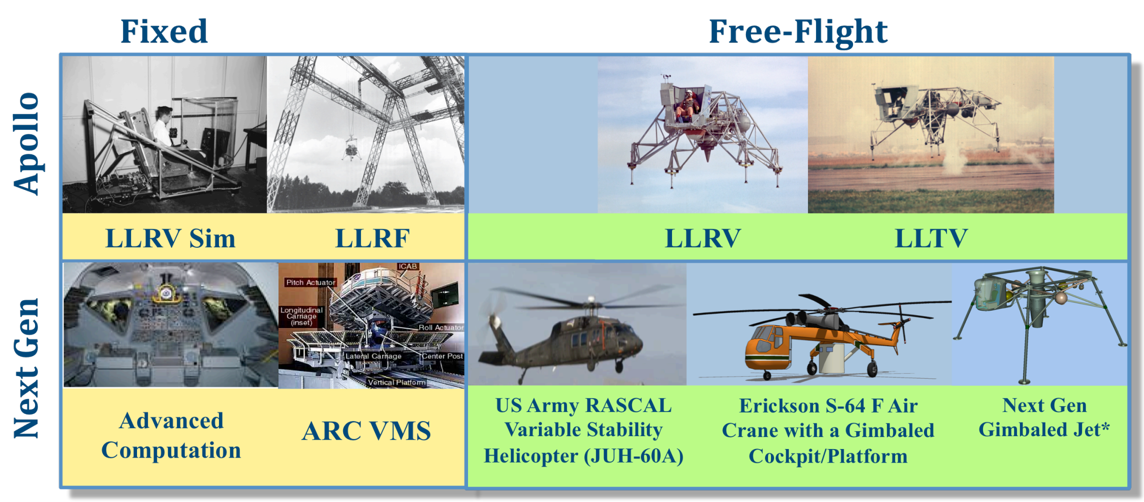

Figure 2 Applying the Past Successes to the Future

The Apollo experience strongly emphasizes the high value of the confidence gained in the pilot's ability to handle the strange and unfamiliar behavior of a VTOL during the final approach in the $1/6^{th}$ g environment. This will still apply to other fractional *g* environments.

3. The Choice of a Free-flight Simulation System

Within NASA's human space flight program there are two landing training systems from which to draw experience, the Shuttle Training Aircraft (STA) and the Apollo Lunar Lander Training Vehicle (LLTV). The two landing training systems, just like the two spacecraft associated with them, are vastly different from one another and perform two very different missions. The STA is used to train for the two-dimensional, horizontal Earth-landing task of the Space Shuttle. The

LLTV was used to train for the three-dimensional, vertical Moon-landing task of the LM. Certainly, the most analogous training system to the proposed landing research/training vehicle is the Apollo LLTV system, because the LM and the spacecraft landers for destinations beyond LEO will all land vertically. In fact, inputs from the Apollo commanders who flew the LLTV suggest that many of the elements of the LLTV training system are *best* suited, both physiologically and psychologically, to training for this type of mission. Additionally, they gave inputs that some of the elements of the STA training system may actually *detract* from training for this type of mission. So, the approach taken for a free-flight simulation system is important.

Clearly, the LLTV training system was successful. The correct point of departure for the next generation space vehicle VTOL training system is the LLTV, and not the STA. The question remains, can some of the elements of the STA approach to training add benefit to the LLTV approach? Much has been said about this in discussion with the Apollo astronauts, and some of the their inputs are highlighted below. Detailed synopses of the Apollo astronauts' inputs are shown in Appendix A.

3.1. Space Shuttle Landing Training Philosophy

Shuttle pilot training for landings include fixed base Full Task Trainer (FTT), motion based VMS (Vertical Motion Simulator), T-38 familiarization flights and free-flight Shuttle Training Aircraft (STA). The STA was developed before the first shuttle flight and has been used throughout the Space Shuttle program to train both the shuttle commanders and co-pilots, requiring 1,000 and 500 landings for each mission, respectively. An instructor pilot, an flight engineer, and recording equipment are all on-board the STA to provide accurate training performance for each landing. Landings are practiced at Cape Canaveral, Edwards AFB, and White Sands for each flight.

The STA training system is built around the notion of real-time one-on-one training between the instructor and the pilot. The instructor pilot also serves as a safety pilot. On the Space Shuttle, the relationship between Commander and pilot is similar to the STA model. This has proven to be an effective landing training system for the Space Shuttle program.

3.2. Apollo Landing Training Philosophy

The Apollo lunar landing training required an array of fixed base simulators focused on procedures, helicopter familiarization flights, flights in the NASA Langley Lunar Landing Research Facility, and flights in the Lunar Landing Training Vehicle starting with jet engine and rocket ground firing tests. Also, all commanders were required to operate the c.g. fixture closed loop attitude control system test hot firing the pitch and roll control systems. The nominal syllabus required 22 flights in the LLTV plus periodic refresher flights required by launch schedules. The LLRV/LLTV was one pilot, one vehicle, one landing, and no reset button. The LLRV/LLTV allowed for re-designation of landing sites, which proved to be crucial on Apollo 11.

3.3. Apollo vs. STA

NASA DFRC set out to develop a scoring criteria/categories based on the STA model for use in this trade study. This scoring criteria was modified through discussions with the Apollo Expert Panel Review and applied in Section 3.

The X-15, lifting bodies and the Space Shuttle are all low L/D vehicles landing on runways, a basic 2-D piloting environment. A free-flight variable *g* landing research vehicle is in a 3-D environment, a totally different set of challenges for the pilot. The presence of an instructor pilot aboard a variable *g* free-flight landing research vehicle has the psychological effect which erodes the confidence gained by the Apollo commanders that they can do the job alone. It also increases the risk, cost, and reduction of payload by requiring two ejection seats in a VTOL environment. Also a two-seat configuration places two pilots at risk and could complicate vehicle command and control in the final seconds of landing approach.

There is an opposing view from an experienced STA instructor pilot who feels strongly that undue training risk is present for a variable *g* trainer without an instructor pilot or ample fuel reserves. These two issues need to be addressed as part of the proposed Advanced Landing Technology Development and Training Program. For a flight research vehicle, there is no justification for two pilots.

Future decisions regarding the presence of a safety pilot to reduce training risk while, according to the Apollo inputs, increases mission risk should be based on an extensive flight research program that addresses all the psychological and physiological aspects of the landing mission. There were many pertinent inputs from the expert panel review and others . . . outlined below. A complete transcript is presented in Appendix A.

3.3.1. Gene Cernan on the fundamental difference between STA and LLTV

"You said a minute ago, which ones, the most important that you prepare for, that you're most focused on, it's the first one, it's your first shot and that's what I'm trying to say, you don't have a reset button in an LLTV, you don't have a reset button in a lunar lander. That's the first landing, its got to be the one you focus on and the fact that you don't have a guy you can … a safety pilot to save your butt, the fact that you can't say, stop the world, I want to talk about this thing I just messed up on, you don't have that, you've got… I mean it's a philosophical thing but you brought it home to me when you said, I'm going up to make ten landings in the STA, but, man, this is the one that's going to count, the first one, that's the one you've got to make happen. And the LLTV puts you in that psychological environment, I'm up here, I've got to make this landing, and ain't anybody else going to make it for me and that's where you are when you're on the moon. So, based on the input of those who have successfully landed on the Moon, the fundamental approach to the training system is critical. As such, deference is made in this paper to the LLTV training approach when considering the technical merits of each of the landing simulator concepts."

3.3.2. Gene [Cernan] do all you can

Gene Cernan: This [variable stability] helicopter last thing came potentially closer, but I think if you had the ability to go …, I'm not even talking about cost, but the ability to go one step closer to the real world, you ought to take it. It's too important of a trip. You've got too much at risk; you've got too much hanging out there. You ought to do as much as you possibly can within the earth environment to simulate the real world as you possibly can. Within your confines of cost and risk and however else you want to put all of them in a pot to evaluate.

3.3.3. gene risk here not on the moon

Gene Cernan: … and all the crew source training and management, I'd stack what Jack and I did in the simulator against up anybody working together problem solving in dynamic simulator environment condition, you don't have time, you can't get that, you don't need to get that on a quote LLTV. I heard things about risk, you know John said we'd crash two or three more before we got to the moon on Apollo 20, maybe he's right, I don't know. I'd rather put myself in that risk environment here to give myself the confidence that I can handle it in the same risk environment, its worth it. I don't want to put him in it with me.

DRS [Dave Scott] Comment: The LLTV risk environment on Earth is far less than the lunar lander (LM) risk environment at the Moon. In the Earth environment, the situation is under better control, and it is shorter term with a simpler vehicle. And at the Moon, both the mission and the crew are at risk – a risk that can be reduced by having a qualified and proficient pilot at the controls. Only an LLTV-type vehicle that very closely replicates the LM can provide the qualification and capability necessary for a successful lunar landing (Note D).

Note D: The experience. Landing on the Moon is a brief, and very unforgiving, experience. Many factors are involved – each and every factor must be considered and evaluated continuously. These factors include vehicle dynamics and motion, control and handling qualities (including response time), landing point selection, time available, control systems operation, computer operation, and the operations of all of the other many vehicle systems. Therefore, it is essential that as many of these factors be integrated into the pilot's training and proficiency as possible.

What's the task of a free-flying Lunar Lander Training Vehicle? (A) To place the pilot in the control loop as an active (direct) and feedback element. (B) To condition (train) the pilot in the highly dynamic and short time-constant flight operations. (C) To enable the pilot to readily and comfortably enter an effective performance "zone" during landing operations ….

Pilot qualification and proficiency. Not only must the pilot demonstrate qualification in the LLTV, but the pilot must also demonstrate a high degree of proficiency in the LLTV. Otherwise, the pilot will not be suitable for a lunar landing (see also Note L.) As the old adage reminds us:

> Aviation itself is not inherently dangerous.
> But like the sea, it is terribly unforgiving
> of any carelessness, incapacity, or neglect.

And the STA, albeit a very good trainer should not be used for analysis or comparison – the capabilities, objectives, and training benefits of the STA and the LLTV are entirely different. As examples, Shuttle approach and landing can be simulated in various aircraft (systems and procedures in other simulators); whereas the LLTV training for lunar approach and landing is absolutely unique (no other trainer, including Langley, could be used for this objective).

Note L: The responsibility of senior management is to ensure the highest probability of success of the mission coupled with minimum risk of loss. The LLTV-type vehicle (LLTV) itself contributes to both. But the pilot of the Lunar Lander (LM, Altair, etc.) must be proficient in the LLTV; that is he/she must have demonstrated – repeatedly - very high-quality flying capabilities and flight-management skills. <u>To send somebody to land on the Moon (planet, etc.) who has not proven him/her-self in an LLTV-type vehicle would be irresponsible</u> – that is, without demonstrated capability in the LLTV, a non-qualified pilot would lower the probably of success and increase the overall risk of the mission.

To quote Pete Conrad: "*We are banking our whole program on a fellow not making a mistake on his first landing.*" *Digital Apollo*, David A. Mindell, MIT Press 2008 (p 181).

<u>Note K. 2nd (Safety) Pilot [On a Second Pilot]</u>
<u>Gene Cernan:</u> I'm not against it, all I'm saying is if you want to throw a safety pilot in the system, throw him or her in. I'd be careful, (I use the word him generically.) If you want to put a safety pilot in the system, put it in, if you can afford it, makes it less risky, that's fine, all I'm saying is you're giving up, you're giving up a valuable part of that simulation and it's the psychological affect of taking you one step closer, by yourself, without mission control, by yourself, one step closer to the real world of landing on the moon, that's all I'm saying. That's me; other people may disagree with me. Put a safety pilot in, fine, you reduce your risk, you gain safety, you spend more money, but you also lose of that what I think is a very valuable part of the LLTV simulation and that's having to do it.
<u>Wayne Ottinger:</u> And you could increase mission risk because you did it that way.

<u>DRS comment</u>. The LLTV does put you on the line and it forces you the think the lunar landing profile (Note J) – it does not have a reset button such as a simulator, but it does have a breakout capability to exit the lunar sim and then land in a much easier and safer mode. A safety pilot actually increases risk (see Note K).

Note K: I strongly favor the solo LLTV configuration (pilot only) for the following reasons, among others:

1. What would the 2nd (or "safety") pilot do?

   - Call out corrections? (and interrupt the pilot – the Flight Director can communicate systems problems).
   - Make comments during an intense maneuver? (and slow the pilot's thought process – the pilot should not be distracted by 2nd pilot opinions)
   - Act as the LMP? (The LMP gets his training in the LMS; and the PILOT must be able to land without LMP communications anyway)
   - Grab the controls if he does not like the situation?
   - Get a thrill; be frightened.

2. What controls and displays would be added for the 2nd seat? What overrides? All of which would need to be integrated into the total system and result in additional failure modes, more complex mission rules, and more complex flight operations.
3. Adding a 2nd place will increase cost, schedule, and most importantly risk – for no recognizable return (that is, it is unlikely the 2nd seat would add anything meaningful to the training, and indeed subtract from it).
4. No time to do anything that would contribute to safety (but could detract from safety).
5. Distracting to the pilot.
6. Might provide reliance by the pilot in certain situations where the pilot should make the decisions rather than rely on a safety pilot – thus perhaps providing a false sense of security
7. Communications might conflict with and confuse the comments from the Flight Director (who would have much more data)
8. Pilot decisions must be based on the task at hand; and not based on having a passenger for which the pilot is ultimately responsible.
9. How many of the 2nd seat people would have survived the three losses of the LLTV during Apollo?
10. Certainly not going to give the 2nd seat the trigger to eject.

Remember that the LLTV pilots are not (should not be) beginners; they should already be comfortable in solo checkouts of new and/or high performance flight vehicles (e.g., grads of a recognized TPS).

3.3.4. Summary of STA Comparison to a partial *g* vertical landing simulator

The initial advice from the NASA JSC crew office suggested modeling portions of a new lunar landing training syllabus after the STA. After inputs from the Apollo crews, there were less useful applicable STA characteristics than originally thought. The most significant Apollo input is the immense value of the psychological environment. The confidence building was that they learned to make the real landings under short fuel conditions and no reset button. They learned to cope with the high attitude angles required and accompanying delays in translation maneuvers in the 1/6th g free-flight simulation environment. The following excerpts from the Apollo crew on 12/9/08 address this.

3.4. Inputs From the Apollo Commanders

3.4.1. Neil Armstrong (Apollo 11 Commander)

“The LLTV if made today I would hope is an order of magnitude better in both performance and reliability so on than it was in our time. Should be and it will make a big difference…..”.

“Apollo Eleven’s running short on fuel is widely known, and has been widely discussed by the press and others and even in mission control here, people were biting their nails…. I had been flying the machines at Ellington; we took off with nine minutes of jet fuel and someplace between ninety and a hundred seconds of rocket fuel. So we were always landing with twenty, or fifteen or twenty or twenty five or 30 seconds, we had to – and so it wasn’t very much of a concern to me in Apollo Eleven because it was just like I was used to and if I made a mistake it would be a bad one. So I think that was a … Dave Scott thinks this was one of the more important aspects and one that I haven't really though much about. He does think that is an important experience to make yourself have the mindset to be comfortable in a short fuel situation."

3.4.2. David R. Scott (Apollo 15 Commander)

See section 2.333 above

3.4.3. Gene Cernan (Apollo 17 Commander)

"Neil says it exactly the way I feel; you know to me its one step closer to the real world. You are out there at four or five hundred feet, you got five minutes of fuel, fifteen, whatever the hell it is, its only a you and your maker, OK. You're running a problem in an LMS in a simulator, you have a problem, you go topsy into a crater, push the freeze button, let's go on and have a cup of coffee and talk about it. When you are in the environment Neil is talking about, you don't have a freeze button. You are going to either do it or not do it, and I want to know that I can do it and feel comfortable before I get out there two hundred and fifty thousand miles away and have to do it one time successfully. I think putting yourself in that environment, quote, a risk environment, you know John [Young, Apollo 16 Commander] is right, I don't want to crash an LLTV, but I would rather have the option of screwing up here and learning something and getting out of it and doing it again, because I don't have that option when I am landing on the moon. And so its not … there is a lot of psychological effect to the comfort level I think we gain when were in that real world in a lunar module, landing on the surface of the moon that we gained because of the environment we found ourselves in the LLTV."

3.4.4. Armstrong and Conrad in *Digital Apollo* (David A. Mindell) [1]

Armstrong and Conrad were unequivocal. "Were I to go back to the moon again on another flight," Conrad asserted, "I personally would want to fly the LLTV again as close to flight time as practical." He felt the computerized lunar mission simulator was not adequate for training for the last 200 feet of the landing, nor was a large gantry-frame device built at Langley. By contrast, the LLTV gave him a good intuition for pitch attitude, which was difficult to perceive on the LM. For his Apollo 12 landing, Conrad had to make some rather radical maneuvers, pitching the LM over nearly forty degrees in a steep descent, but the confidence he developed with the LLTV allowed him to fly with no concerns. "We are banking our whole program on a fellow not making a mistake on his first landing," Conrad emphasized, and the LLTV helped a pilot with a valuable but immeasurable quality: confidence.
Armstrong, as usual, chimed in with fewer words, but supported Conrad's conclusion. He recalled the LLTV's value in helping him perceive subtle variations in lateral velocities, and in imposing the discipline of time pressure. The LLTV helped him learn how to select alternate landing areas. During training, he said, "You sort of play the game with yourself, as you fly into a touchdown area and you say no, I don't want to land there—I want to land over there." That game, related Armstrong, provided "the confidence in your own knowledge that you can fly the job in." A landing accident would be catastrophic to the entire Apollo program, and the LLTV was like an insurance policy, he said, noting, "my own conclusion is that we still can't afford not to insure against this particular catastrophe."

Astronauts always supported the LLTV, and it supported them: showing lunar landing to be a difficult, risky endeavor of machine control that could be mastered by confidence, experience,

[1] Realism, Risk, and Confidence Page 214

and skill. Several Apollo commanders actually mentioned the LLTV training on the radio during their lunar landings. Nearly all discussed it in post flight briefings as support during the last critical seconds when they took over semiautomatic control.

4. Final Scoring Metrics

The scoring matrix criteria shown in Figure 3 below were used to provide the rankings of each of the five vehicle platforms selected for this study. Scoring metrics have been developed in order to make an absolute valuation of each landing simulator concept and to make a comparative evaluation of the concepts together. The six categories of metrics by which the concepts are evaluated are:

- Lander Development Support
- Training Effectiveness
- Simulation Fidelity
- Safety and Reliability
- Cost and Availability
- Maintainability

Each category is described in the sections below. Weighting factors for each of the scoring metrics have not yet been established. However, in terms of relative importance (weighting), the Training and Simulation Fidelity metrics are most important and must be weighted the highest. The Safety and Reliability, Maintainability, and Cost and Availability metrics are weighted lower.

4.1. Scored Matrix and Color Code

Figure 4, Scored Matrix for Five Candidate Vehicles, is based on current knowledge, but may change if near-term refined studies performed for the Gimbaled Jet, Air Crane (& Flight Test), and the Variable Stability Helicopter are performed. The adaptation of the existing proprietary design work performed by Orbital Sciences on the gimbaled jet, the conduct of a few test flights of the Air Crane, and further study of the Variable Stability Helicopter will provide the baseline needed for NASA to launch a sound new technology development program and lay a foundation for future landings beyond LEO.

Table 1, Detailed Metric Comments, further describes the advantages and limitations of the candidate vehicles.

	Spacecraft Lander Development Support	Training Effectiveness	Simulation Fidelity	Safety and Reliability	Cost and Availability	Maintainability
Green	Provide high level DDT&E Support for spacecraft development.	Psychological effectiveness including motion cues, single pilot, veh. attitudes.	Simulation accuracy including de-couple from earth g, drag compensation.	Historical basis for both pilot and vehicle.	High confidence in design/development providing two research vehicles in the area of $100 million; generally available.	Similar to fixed wing aircraft, no special handling.
Yellow	Provide good DDT&E support for spacecraft development	Dual pilot and some negative or incomplete training.	Degraded accuracy or potential for negative training.	Moderate risk based on anticipated hazard analysis.	Design/development projected for two research vehicles in the area of $150 million; available with difficulty.	Increase in maintenance & logistics over fixed wing aircraft.
Red	**No significant DDT&E support**	**Many negative training elements**	**Inability to decouple from earth g and/or aero forces**	**Landing simulation mission unsuitable.**	**Over $200 million for two reservh vehicles; generally unavailable.**	**History of high maintenance and logistics.**

Figure 3 Category Scoring Criteria

	Spacecraft Lander Development Support	Training Effectiveness	Simulation Fidelity	Safety and Reliability	Cost and Availability	Maintainability
Gimbaled Jet (Apollo Legacy)	Best free-flight for pilot i/f, Closest to real-world dynamics	Apollo Legacy, six good landings, well trained pilots	Ingenious sensor design , .005 g accuracy	Comparable to other new aircraft dev.	$100- 150 million, 2 yrs	High-end Helicopter
	Limited payloads			3 of 3 safe ejections, known fixes	more than Air Crane, not major	
S-64F Air Crane	Larger margins & payloads proven before gimbaled jet tries it.	Multiple crew, psychological deficiencies	Potential accuracy, expanded envelopes	48 yrs flying fire missions match needs for landing simulations	Lease available, risk reduced, incremental & phased development	High-end Helicopter
	No rocket dynamics, accuracy legacy		Flight Dynamics & Accuracy TBD, Potential VRS			
Variable Stability Helicopter	Sensor closed loop testing, pilot interface & visibility	Two Pilots, Pitch cannot be de-coupled from g offset	Pitch not de-coupled from g offset, Pot. VRS	Mature Development	Lower than Air Crane or Gimbaled Jet	Helicopter
V-22 Osprey Tilt Rotor		**Too many deficiencies**				
AV- 8B Harrier VTOL		**Too many deficiencies**			**Availability in question**	

Figure 4 Scored Matrix for Five Candidate Vehicles

Table 1 Detailed Metric Comments

Vehicle		Remarks
Gimbaled Jet	Development Support	Apollo legacy for spacecraft lander development support. Excellent ROI for spacecraft DDT&E.
	Development Support	Limited to flight hardware payloads as opposed to heavy laboratory payloads
	Training Effectiveness	Apollo legacy, psychological and physiological, 6 good landings, well trained pilots.
	Simulation Fidelity	Ingenious sensor design concept .005 g accuracy for both earth g offset & aerodynamic drag comp.
	Safety & Reliability	Safety record commensurate with other new aircraft developments, matured quickly in comparison.
	Safety & Reliability	Crew resource management error on first two accidents and the third an unidentified electrical failure mode, all three excellent ejection seat performance, no significant injuries
	Cost & Availability	Apollo design upgrade with new technology, particularly new jet engines, avionics, and structures can be flying in 2 to 2 ½ years for about $100 - 150 million
	Cost & Availability	Initial cost of the upgraded gimbaled jet will be more than the Air Crane, but life cycle costs are likely to be similar due to the high operating costs of the Air Crane.
	Maintainability	Maintainability equivalent to high-end helicopters
Air Crane	Development Support	Expanded margins for experimental system testing and payload capability with extended sortie times makes this a flexible flight research platform
	Development Support	Experiments requiring the closest match possible to the real spacecraft lander dynamics including rocket control systems for lift and attitude control should be deferred to the gimbal jet
	Training Effectiveness	Multiple crew members, pitch up visual impairment, psychological deficiencies
	Simulation Fidelity	The potential accuracy and ability to test both sensor and pilot interface for controls, displays, and visibility with expanded envelopes not suited for the free-flight gimbaled jet makes this an attractive platform.
	Simulation Fidelity	Flight test confirmation of flight dynamics and trajectory simulation accuracy needs to be established.
	Safety & Reliability	Outstanding safety and reliability record, with its fire-fighting mission a good legacy for the VRV .
	Cost & Availability	Lease OK, investment is in cab, controls, software, incremental phasing of development reduces risk.
	Maintainability	Maintainability is high-end helicopter maintenance.
VSS Helio	Development Support	Some limited support for early tests of sensor and control system. Also, pilot interface and visibility developments.
	Training Effectiveness	The inability of the helicopter to decouple pitch attitude from the earth g offset and the dual pilot configuration constrains the effectiveness.
	Simulation Fidelity	The inability of the helicopter to decouple pitch attitude from the earth g offset constrains the effectiveness. Flexibility of cockpit arrangement is limited.
	Safety & Relaibilty	Mature Navy VSS development makes it a good choice for initial training for VTOL operations.
	Cost & Availability	This will not require the development costs compared to the Air Crane or gimbaled jet.
	Maintainability	Helicopter maintenance substantially more than fixed wing.
V-22		**Too many deficiencies for the mission**
AV-8B		**Too many deficiencies for the mission**

4.2. Training Effectiveness Metric

There is an aspect of training that goes beyond fidelity. One can have all of the cues right, all of the visuals right, etc., but still miss something critical to the effectiveness of the training. Gene Cernan summarizes succinctly "you have to eject or land, those are the only two options". Think of it with this analogy: the ultimate training to learn how to fly an aircraft is to go fly the aircraft. For a Moon lander or other destination beyond LEO, there is no such analog. You work with the next closest thing you can in an Earth analog: an Earth lander. But, just as in the airplane, you have to make the landing. Something beyond the fundamentals of the physics needs to be put into the *psychology* of the task. "I must make this landing–I can't rely on anyone else. If I don't make this landing, really bad things are going to happen." So, in this case, the fidelity of the *physics* is not nearly as important as the fidelity of the *psychology.* So, physical effectiveness is important, but psychological effectiveness is also very important and must be taken into account. That is why this metric is here. There is something in the concept, "training with real consequences", that is meant to be captured here.

The Training Effectiveness scoring metric was established as a direct result of the Expert Panel Review. The Training Effectiveness metric is intended to capture the *effectiveness* of the landing simulator concept as a training system, whereas Simulation Fidelity is intended to capture the *fidelity*. As such, the metric should capture the *psychological* and *physiological* effectiveness of the concept. A good landing simulator is both a piloting skills trainer as well as a system to put the trainee psychologically "there". Ultimately, proficiency, confidence and mental comfort in performing the real landing task are the aim of the training system. As a consequence, the training system should minimize *negative training* and *habit intrusion* to the trainee, where, as a product of the training system itself, the trainee is being habituated to perform tasks or respond to inputs in a manner that are not consistent with real system.

4.3. Simulation Fidelity Metric

Related to Training Effectiveness is Simulation Fidelity. Whereas Training Effectiveness is a measure of how *effective* a training system is, Simulation Fidelity is measure of how *accurate* the training system is compared to the real or expected system. In terms of accuracy, there are several aspects of simulating the real system that are important:

- Pilot task recreation
- Trajectory recreation (includes accurate attitudes accounting for aerodynamic moments)
- Translational and rotational dynamics (includes aerodynamic moment offsets)
- Gravity offset
- Motion cues
- Field of view
- Cockpit layout

For trajectory recreation, it is only important to recreate that part of the trajectory where pilot skills are crucial to a successful landing. The Apollo astronaut inputs indicated this to be about the last 500 feet to landing, which would include re-designation maneuvers.

4.4. The Other Metrics

The other metrics are not discussed in detail here but are summarized in Figure 2 Category Scoring Criteria.

5. V*g*LRV Vehicle Concepts

Based on the crew training and vehicles objectives previously established, several free flight vehicle configurations are under consideration. Of principle importance is the necessity to provide the free flight vehicle with a means to simulate lunar gravity by means of an auxiliary lift device, where such a device must remain vertical as the training vehicle rotates and translates. As discussed in the original Bell Aerosystems feasibility study [Ref. 2], the vehicle center of gravity and the auxiliary lift device center of gravity must also coincide. This requirement, coupled with the necessity to support a vertical landing leads to the development of three major categories for a V*g*LRV configurations under consideration:

1. Gimbaled Jet
2. Helicopter
3. VTOL or STOVL Aircraft

5.1. The Apollo Gimbaled Jet

In 1962, the gimbaled jet approach to free-flight lunar simulation matured into the Lunar Landing Research and Training Vehicle Programs. The LLRV/TV design incorporated reaction control rockets for control and larger rockets for lift, while utilizing a gimbaled jet engine for gravity offset and for aerodynamic drag compensation. This unique configuration (Figure 5) proved to be accurate within .005g in both the vertical axis for lunar g simulation as well as for all three axes of aerodynamic drag compensation. It is likely that no other simulation concept can match the fidelity of the gimbaled jet for earth-bound free-flight lunar simulation. The six Apollo landings confirmed the fidelity of the earth-bound simulation that was provided by the gimbaled jet concept [Ref. 12].

Orbital Sciences Corp. has conducted an extensive internal study of the Gimbaled Jet concept including research into the original Apollo design, trade studies to meet modern Altair requirements, and specific upgrades and enhancements to increase safety and reliability. A summary of Orbital's work to-date is included in Appendix J. The current gimbaled jet concept is based on the original LLRV/TV design, where a vertically mounted turbine engine is used to provide the gravity and aerodynamic drag compensation. The main propulsion system is hydraulically gimbaled to remain vertical through all the required pitch and roll attitudes, except for small off-vertical rotations to compensate for drag. Jet engine auto throttle adjustment offset vertical drag. Thrusters, mounted externally on the same structure common with the cockpit replicate the descent engine thrust as well as attitude control. Such thrusters may be liquid rocket systems utilizing hydrogen peroxide, as used by the original LLRV/TV, or may utilize more advanced systems currently being analyzed for feasibility. The flight control system is a digital closed loop system with inputs from motion sensors and lunar maneuvering thruster measurements for drag compensation to nullify aerodynamic effects. Significant modernization and modifications are under consideration to provide increased safety and operational endurance over that of the Apollo-era LLRV/TV.

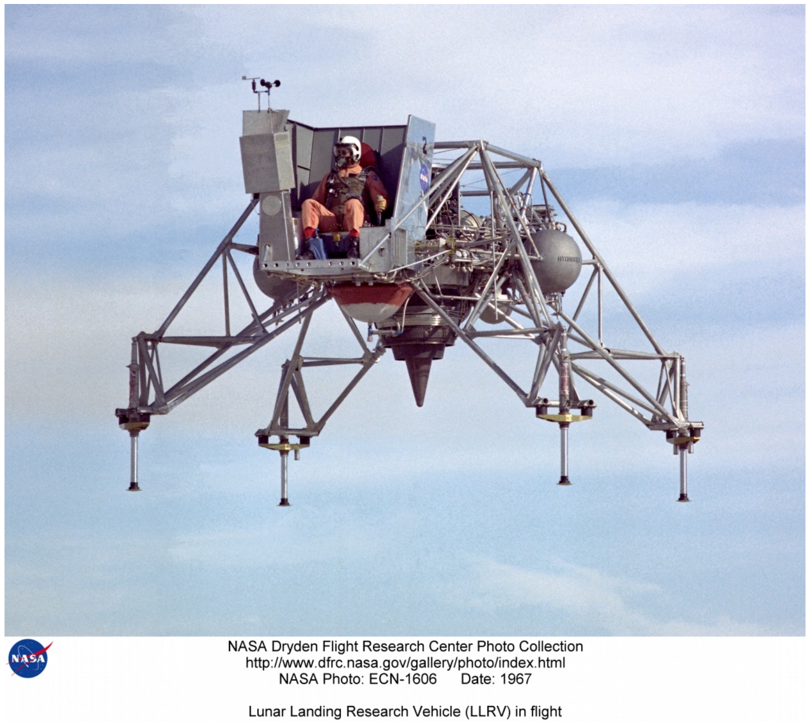

Figure 5 Apollo Era Gimbaled Jet Design

5.1.1. Next Generation Gimbaled Jet

	Spacecraft Lander Development Support	Training Effectiveness	Simulation Fidelity	Safety and Reliability	Cost and Availability	Maintainability
Gimbaled Jet (Apollo Legacy)	Best free-flight for pilot i/f, Closest to real-world dynamics	Apollo Legacy, six good landings, well trained pilots	Ingenious sensor design , .005 g accuracy	Comparable to other new aircraft dev.	$100- 150 million, 2 yrs	High-end Helicopter
	Limited payloads			3 of 3 safe ejections, known fixes	more than Air Crane, not major	

5.1.1.1. Spacecraft Lander Development Support

Provide high-level DDT&E Support for spacecraft development:
The gimbaled jet has the inherent capability of replicating the dynamics and motion cues for rocket attitude and lift control systems, can be designed to accommodate significant payloads for testing closed loop guidance and control hardware as well as displays and cockpit controls. All of these capabilities include the ability to offset accurately the selected earth g excess gravity and the aerodynamic effects for flying on the earth.

5.1.1.2. Training Effectiveness

Something beyond the fundamentals of the physics needs to be put into the *psychology* of the task. "I must make this landing–I can't rely on anyone else. If I don't make this landing, really bad things are going to happen." So, in this case, the fidelity of the *physics* is not nearly as important as the fidelity of the *psychology*. So, physical effectiveness is important, but psychological effectiveness is also very important and must be taken into account. That is why this metric is here. There is something in this concept, "training with real consequences", that is meant to be captured here.

The most ideal Earth-bound training would have to land a spacecraft lander for destinations beyond LEO on the Earth's surface. The Training Effectiveness scoring metric was established as a direct result of the Expert Panel Review. The Training Effectiveness metric is intended to capture the *effectiveness* of the landing simulator concept as a training system, whereas Simulation Fidelity is intended to capture the *fidelity*. As such, the metric should capture the *physiological* and *psychological* effectiveness of the concept. Fundamentally, a good landing simulator is both a piloting skills trainer as well as a system to put the trainee psychologically "there". Ultimately, proficiency, confidence and mental comfort in performing the real landing task are the aim of the training system. As a consequence, the training system should minimize *negative training* and *habit intrusion* to the trainee, where, as a product of the training system itself, the trainee is being habituated to perform tasks or respond to inputs in a manner that are not consistent with real system.

The Apollo gimbaled jet demonstrated the closest replication of both the *physiological* and *psychological* conditions possible for the pilot training for lunar landings. This coupled with the six successful Apollo landings and the consistency of the training received by all the Apollo commanders receiving the training, makes this metric the highest ranking weighting factor in the choice of a training vehicle as well as for a research vehicle platform for DDT&E support of spacecraft development.

Technology advancements since Apollo will further enhance the effectiveness of the gimbaled jet. While building on the simple, yet unique Apollo design of the most direct method of offsetting earth g and aerodynamic forces and yielding a terrestrial free-flight variable-g landing simulator. Figures 6 and 7, shows Orbital Science's concept of a contemporary gimbaled jet utilizing a current jet engine, which has about 50% more thrust than the Apollo LLRV/LLTV thus able to support a larger free-flight simulator in keeping with the larger size spacecraft lander accommodating four astronauts instead of two.

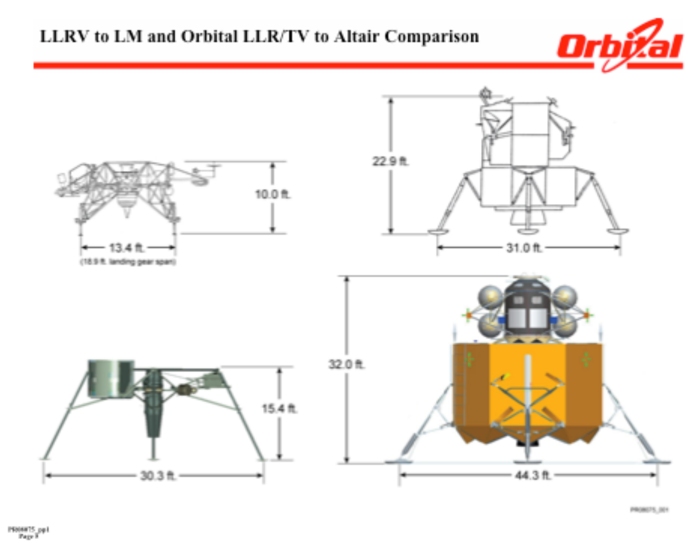

Figure 6 LLTV/LM and Next-Gen LLTV/Altair Comparisons

Orbital Studied the Apollo LLRV/LLTV Design Characteristics and Operational History

Orbital

- Combination of motion sensors and gimbaled jet yielded .005 g accuracy for earth g and aerodynamic drag compensation, providing high fidelity training
- In depth study of safety and reliability of the Apollo LLRV/LLTV demonstrates ample opportunity for improvement in both design and conduct of flight operations
- Orbital has a conceptual design developed utilizing today's off the shelf hardware and technology capabilities to fast track the development of a scaled up version of the Apollo LLRV/LLTV to a new Altair LLR/TV

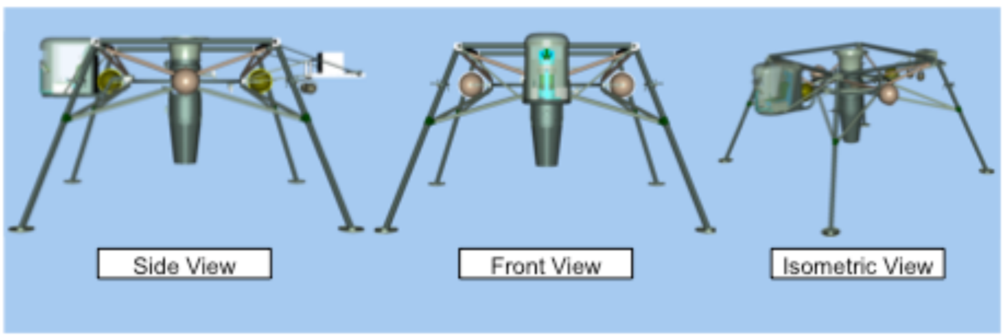

Figure 7 Orbital's Conceptual Design

Figure 8 shows the trade-offs for using a remotely piloted vehicle vs. a piloted vehicle.

RPV Can't Do the Job by Itself

Orbital

Piloted		RPV then Piloted	
Advantages:	**Disadvantages:**	**Advantages:**	**Disadvantages:**
At least half of DDT&E mission involves pilot in the loop.	Slight increase in risk for pilot on first flights (This is acceptable based on Apollo experience and ejection seat)	Initial risk reduction for pilot in the loop	Loss of pilot interface portion of DDT&E mission.
Less risk to loss of vehicle based on Apollo experience.			Increased risk to loss of vehicle
Avoids a longer DDT&E schedule.			Schedule, for RPV preceding pilot in the loop.
Less costly			Cost, for RPV preceding pilot in the loop

Figure 8 Piloted vs. RPV (Remotely Piloted Vehicle)

5.1.1.3. Simulation Fidelity

Related to Training Effectiveness is Simulation Fidelity. Whereas Training Effectiveness is a measure of how *effective* a training system is, Simulation Fidelity is measure of how *accurate* the training system is compared to the real or expected system. In terms of accuracy, there are several aspects of simulating the real system that are important:

- Pilot task recreation
- Trajectory recreation (includes accurate attitudes accounting for aerodynamic moments)
- Translational and rotational dynamics (includes aerodynamic moment offsets)
- Gravity offset
- Motion cues
- Field of view
- Cockpit layout

For trajectory recreation, it is only important to recreate that part of the trajectory where pilot skills are crucial to a successful landing. The Apollo astronaut inputs indicated this to be about the last 500 feet to landing, which would include re-designation maneuvers.

The Apollo gimbaled jet accuracy of .005 g for earth g offset and aerodynamic forces together with the pilot task recreation, trajectory recreation, dynamics, motion cues, field of view, and cockpit layout all worked together to make it the closest possible free-flight simulation available at the time. This is likely to be enhanced with new technology building on the Apollo gimbaled jet design.

5.1.1.4. Safety and Reliability

With respect to safety and reliability, the gimbaled jet design is, unfortunately, subject to criticism due to the loss of three vehicles during the Apollo era, although 795 successful flights were conducted at both the NASA Flight Research Center and Ellington Field. The loss of LLRV No. 1 is attributed to the inadvertent depletion of the helium tanks required to operate the attitude control thrusters. Potential concepts will incorporate positive expulsion devices to eliminate the loss of pressurant failure by placing a physical barrier between the pressurant and the propellant. Additionally, this device will have the added benefit of providing in flight wet center of gravity management through active fuel tank balancing controls as well as real time propellant remaining indications through a feedback mechanism.

LLTV No. 2 crashed due to the loss of electrical power to the flight control system. Later reports indicated that this accident was due to an upgrade in the DC generator of the jet engine, which resulted in a high residual magnetic field upon failure, preventing switchover to the emergency electrical bus. This could have been easily prevented with a design correction or modern battery technology [Ref. 12]. This loss, along with the loss of LLRV No. 1, showed design deficiencies as well as monitoring deficiencies that were corrected and can be avoided in future gimbaled jet designs.

The loss of LLTV No. 1, conversely, is attributed to operation outside the vehicle's limits. A complete understanding of the operational limits of the vehicle as well as the inclusion of a modern real time meteorological monitoring station will mitigate the risk of losing another vehicle. Figure 9 details the history of LLRV and LLTV operations, while throwing into contrast several fatal T-38 accidents reported during the same period.

In all three instances the crew escaped unharmed due to the inclusion of an ejection system, which is expected in future designs as well. In addition to the ejection system, future concepts could incorporate a ballistic parachute recovery system, possibly deployed subsequent to crew ejection, to mitigate the loss of the vehicle while ensuring crew safety. Unlike the previous LLTV, any future concept will leverage decades of digital flight control experience. Flight control systems will be redundant, with the possible capability of monitoring critical parameters real time by way of a modern data system, and are expected to utilize a battery backup system in the event of generator failure.

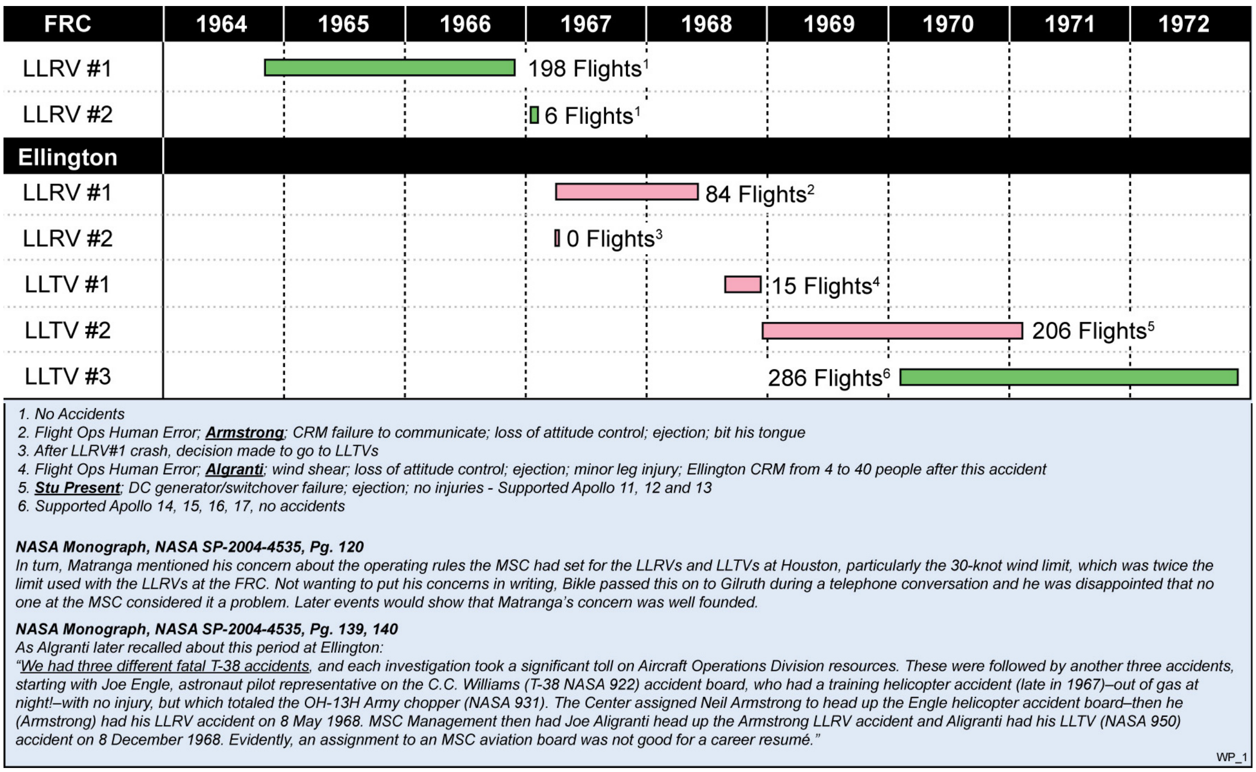

Figure 9 LLRV and LLTV Flight History

Quote from Dave Scott, Apollo 15 Commander

"Historically, upon introduction, new flying machines go through a transition period of learning and experience, which is often characterized by "accidents." In recent times, one of the most advanced flight vehicles ever designed, the F-22, has unfortunately experienced three accidents. One would now expect significantly improved F-22 operations in the future.

During earlier times, and as an illustration based on my personal experience, some years ago I joined a fighter squadron that had an exceptional safety record, with highly experienced pilots, ground crews, and maintenance – over four years of F-86 operations, some 40,000 hours without an accident. We then transitioned into the F-100 – during the next 14 months this same squadron experienced 8 accidents (major and minor); thereafter the operations smoothed out with only 3 accidents during the next 4 years (2 due to ground radar flight control) – a maturity record not unlike the LLTV."

Quote from Neil Armstrong, Apollo 11 Commander
"The LLTV if made today I would hope is an order of magnitude better in both performance and reliability so on than it was in our time. Should be and it will make a big difference…..".

5.1.1.5. Cost and Availability

Green Criteria - High confidence in design/development providing two research vehicles in the area of $100 million.
Yellow Criteria - Design/development projected for two research vehicles in the area of $150 million.
The gimbaled jet, is anticipated by NASA DFRC to provide two research vehicles ready for DDT&E support flight tests in the area of $100 to $150 Million. This design/development program is projected to take two years and include spares for the initial DDT&E flight tests.

5.1.1.6. Maintainability

The gimbaled jet requires maintenance and operations support equivalent to a high-end helicopter, such as the S-64F Air Crane. The Apollo legacy rocket propellant system is 90% hydrogen peroxide (H_2O_2). Today's improvement in materials used for the rocket system components and storage systems are significantly improved, thus eliminating the need to closely monitor and control the temperature of the storage tanks to prevent hazardous temperature levels leading to decomposition. There is however a requirement for protective clothing for operations personnel. It is anticipated that there will be extended down times, up to an hour or more, between flights for refueling operations. Based on LLRV/TV experience, it is expected that 6 flights per day are possible within the standard crew duty day.

There is some potential for future propellant alternatives. One such alternative is a nitrous oxide fuel blend (NOFB) developed by Firestar Engineering LLC. The rationale for examining NOFB propellant technology for LLTV propulsion system architectures includes the promise[1] for enhanced performance as well as possible improvements in safety and cost during ground handling operations. NOFB propellants are non-toxic. The ability to employ non-toxic propellants would potentially reduce ground-handling costs. NOFB propellants are breaking new ground in monopropellant technology and are comparable in Isp performance to bi-propellants (~325s) while allowing for simpler monopropellant feed-system architectures. NOFB's high thermal decomposition limit/material compatibility allows it to be used as an engine coolant (100% of monopropellant as coolant and phase change material) and, because it is self-pressurizing, NOFB systems do not require special feed systems. NOFB propellants are highly throttlable. A two-phase engine design can operate liquid, two-phase, or gas down to <10 psia chamber pressure with 96+% optimal Isp performance over 10x dynamic range in thrust level by only regulating engine feed pressure. More information about Firestar Engineering LLC and NOFB technology can be found in Appendix K.

Potential problems need further examination for Nitrous Oxide N_2O (per Orbital Sciences).

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[1] Although the technology is viable and working hardware has been demonstrated in tests, there is currently no flight qualified NOFB system for this application.

5.2. Helicopters

A helicopter is a natural platform for a free-flight simulation since it is able to perform a vertical landing. However, a helicopter is not well-suited to replicate the transition from approach to landing, because the attitude of the helicopter must be decoupled from its thrust to replicate motions due to the RCS (Reaction Control System) and the lift rockets, while providing gravity offset—the very reason that helicopters were not used during the Apollo era. Additionally, helicopters generally have a significant aerodynamic profile making them susceptible to atmospheric disturbances, such as gusts. Because it is not feasible to have an ejection system in a helicopter, concepts based on a helicopter must conform to FAR 29 crashworthiness requirements for crew survivability. Two helicopter concepts have emerged and will be given further consideration.

5.2.1. Helicopter, S-64F Air-Crane Concept

<table>
<tr><th></th><th>Spacecraft Lander Development Support</th><th>Training Effectiveness</th><th>Simulation Fidelity</th><th>Safety and Reliability</th><th>Cost and Availability</th><th>Maintainability</th></tr>
<tr><td rowspan="2">S-64F Air Crane</td><td>Larger margins & payloads proven before gimbaled jet tries it.</td><td rowspan="2">Multiple crew, psychological deficiencies</td><td>Potential accuracy, expanded envelopes</td><td rowspan="2">48 yrs flying fire missions match needs for landing simulations</td><td rowspan="2">Lease available, risk reduced, incremental & phased development</td><td rowspan="2">High-end Helicopter</td></tr>
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The S-64F Air-Crane concept summary is discussed in this section. A more detailed discussion of the concept is shown in Appendix L. In order to use the Air-Crane as a Free-flight Simulator, an “astropod” is mounted in the large open space below the fuselage (Figure 10). The interior of the astropod is a representative spacecraft lander cockpit. The astropod is actuated to allow both rotation and translation with respect to the Air-Crane fuselage. The pod is capable of rotating to simulate spacecraft lander attitude changes, as well as limited translation to simulate an accurate rotation about the spacecraft lander vehicle center of rotation and compensate for motion due to the rotation of the Air-Crane itself. A model of the spacecraft lander dynamics is computed onboard the Free-flight Simulator, and a model following or dynamic inverse controller is used to command the pod position and attitude to accurately match the motion of the simulated spacecraft lander spacecraft. Additionally, the controller controls the Air-Crane directly to create accurate longitudinal and lateral translations. A global positioning system/inertial navigation system (GPS/INS) system is used to maintain the proper ground track and velocity, compensating for winds, gusts, and aerodynamic drag. The vertical axis of the Air-Crane is commanded to follow the motion of the simulated spacecraft lander model, simulating both the acceleration due to lunar gravity, and the thrust of the descent engine.

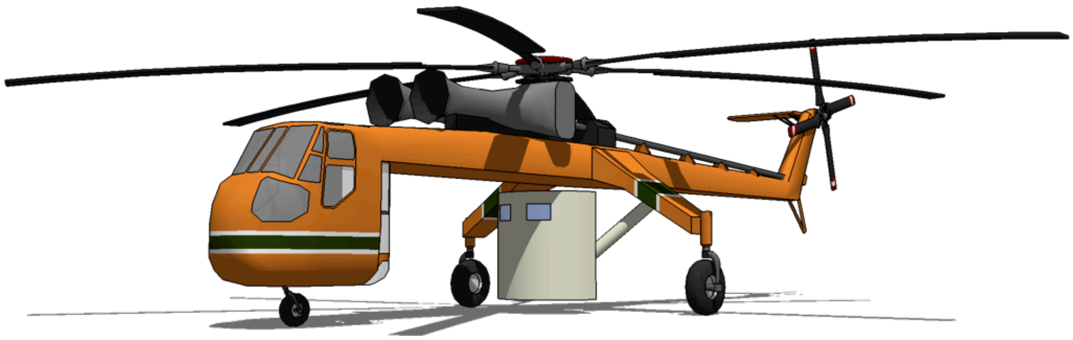

Figure 10 S-64F Air-Crane Free-flight Simulator Concept

5.2.1.1. Spacecraft Lander Development Support

The Air Crane could provide greater payload capability, and provide a build-up of control system margins to establish confidence prior to testing on the gimbaled jet. It can fly for 2 ½ hours and have less sensitivity to surface wind conditions than the gimbaled jet so more testing can be accomplished for systems development. It does not have the ability use rocket systems for attitude and lift controls, but large part of guidance, navigation and control system closed loop testing can be performed, assuming the response times are adequately demonstrated on early flight tests (Appendices D, E, and M).

It is possible to use the Air-Crane for other uses within NASA. The Air-Crane can be used for:

- Primary VTOL training for the astronaut[1]
- Recovery of Crew Exploration Vehicles (CEV) from the Pacific Ocean
- Testing out spacecraft lander flight systems, such as Lidar, cameras, mission computers, life support, etc., a la LLRV
- Rapid prototyping of spacecraft lander pilot-vehicle interface (PVI) and flight control algorithms
- Investigation of spacecraft lander handling qualities, potentially using a dial-a-gain capability
- Spacecraft lander ascent training

[1] Helicopter training was required in the original Apollo lunar landing curriculum

Regarding the potential use of the Air-Crane as a recovery vehicle for CEV, the S-64F has an extended range of 833 km (450 nm) and a maximum payload of 11,340 kg (25,000 lbs). Regarding the potential use of the Air-Crane as an ascent trainer, the CH-54B, from which the commercial S-64F is derived, holds several time-to-altitude records (Appendix C).

As with Apollo [Ref. 15] and Shuttle, it is likely that a continuum of simulation facilities will be used for training and system test. If the non-recurring engineering costs to develop any facility for use as a spacecraft landing trainer can be shared with another facility, then a cost savings may be realized. The modularity of the astropod lends itself to use in multiple simulation facilities. As discussed above, the astropod will likely contain a computer that contains a model of the spacecraft landing trainer dynamics. This astropod /spacecraft landing trainer model combination can be used not only on the free-flying S-64F trainer, but as a standalone ground-based simulator as well as a cockpit for a motion-based simulation, such as the Vertical Motion Simulator (VMS) at NASA Ames Research Center. This simulation continuum is shown in Figure 11.

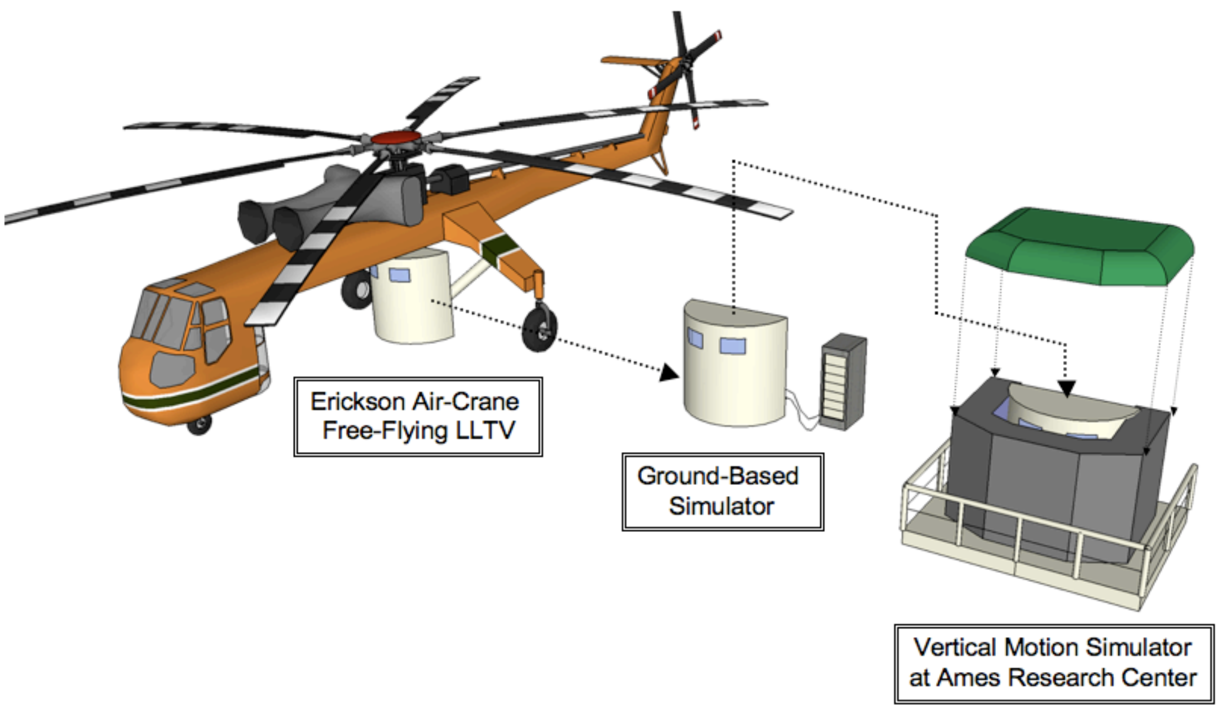

Figure 11 The Astropod Simulation Continuum

5.2.1.2. Training Effectiveness

The dual pilot configuration, the large aerodynamic platform above the astropod, and “reset button” environment with the Air Crane concept all diminish the qualities of training effectiveness as learned from the Apollo astronauts. There is the potential to replicate the cockpit for multiple crew stations which would result in a highly effective training platform even with the negative upper visibility configuration. Therefore, if the simulation is confirmed through flight test to be high, then the Air Crane can be a very effective trainer.

5.2.1.3. Simulation Fidelity

The gimbaled astropod enables the accurate simulation of the spacecraft lander attitude, alleviating the problem of a helicopter's translational velocity being a function of attitude. The decoupling of the astropod from the Air-Crane fuselage should allow for accurate simulation of the spacecraft lander rotations and translations.

It is not clear how well the Air-Crane will be able to match a representative trajectory of the spacecraft lander. The uncertainty is due to the uncertainty of the Air-Crane's dynamic response in the translational axes to produce velocities, as well as the Air-Crane's response to atmospheric disturbances, such as gusts. Erickson Air-Crane does not have a dynamic simulator of the S-64F, so these dynamic uncertainties will be determined through flight test and analysis.

Some encouragement that the S-64F will be able to provide good trajectory fidelity is the S-64F's station-keeping capability and the fact that a large (high inertia) helicopter with high disc loading, such as the S-64F (552 N/m^2 disc loading)[1], is less susceptible to atmospheric disturbances than a small helicopter with low disc loading, such as the Bell 206 Jet Ranger (177 N/m^2 disc loading)[2]. An example of the S-64F's excellent station-keeping ability can be seen in the video of the S-64F lifting the restored Statue of Freedom atop the dome of the U.S. Capitol building.[3]

Since the astropod will be designed to have very similar geometry to the spacecraft lander crew cabin, the cockpit controls and displays, as well as the seating orientation and windows, can be identical to that of the spacecraft lander.

All of these factors, taken together, make the potential score high (green) for simulation fidelity for the Air-Crane concept.

5.2.1.4. Safety and Reliability

The astropod will be built to Federal Aviation Administration requirements for crashworthiness (Federal Aviation Regulation 29). Also, since the S-64F is able to lift 25,000 lbs, it is possible to incorporate many safety features into the astropod design, such as:

- Crumple zones for impact
- Beefed up structural cage to resist crushing
- Crew restraint harnesses
- A fire suppression system
- Air-bags

An aspect of crew survivability that is probably not feasible to build into the design is an astropod jettison or a crew ejection system. Crew safety is therefore dependent on the safety record of the Air-Crane.

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[1] Determined using the maximum gross weight of 47,000lb and main rotor diameter of 72ft.
[2] http://en.wikipedia.org/wiki/Bell_Jetranger
[3] http://www.youtube.com/watch?v=W6kC0cNb31M

Erickson Air-Crane, its affiliates and subsidiaries operate S-64s an average of 16,515 flight hours per year. The incident and accident rate are shown in the table below. If one Air-Crane Free-flight Simulator flies 300 hours per year (roughly 1 hour, or 10 simulations, per day), this incident / accident rate translates to the values shown in the last column of the table.

Table 2 Safety Rate for the S-64F

Safety Category	***Fleet Rate***	***Rate at 300 hrs per year***
Mechanical Incidents	2.4 per 100K hours	1 every 139 years
Accidents	6.05 per 100K hours	1 every 55 years

These statistics speak to the overall safety of the Air-Crane. The vehicle has a redundant power plant. There are two Pratt & Whitney JFTD12-5A turbine engines that can independently drive the rotor transmission.

As with other rotorcraft, the Air-Crane is susceptible to vortex ring state (VRS). A primer on VRS is given in Appendix H. A rigorous analysis will be performed to determine where the VRS region intersects with the Altair trajectories. Flight tests will be performed to investigate the VRS interaction.

Inherent in this concept is the ability to separate the safety pilot function from the instructor and trainee functions. The safety pilot can fly in the S-64F cockpit, while instructor and student fly in the astropod. As with the STA, operational limits for training can be defined and monitored by the safety pilot or flight engineer. Upon exceeding these limits, the safety pilot would disengage the landing simulation and regain control of the vehicle, preventing the Air-Crane from entering an unsafe region of flight. While the safety record of the Air-Crane is excellent, the potential for encountering VRS while flying a lunar landing simulation degrades the score for this category.

5.2.1.5. Cost and Availability

It is anticipated that the total acquisition cost for the S-64F Free-flight Simulator, including modifications (astropod and control system), will be less than $50M. The cost does not include NASA oversight during the development. The operating costs for the S-64F will be comparable to other helicopters of this size.

The Air-Crane aircraft will be available for the foreseeable future. Erickson Air-Crane owns the type certificate for the S-64 family and has full manufacturing and refurbishing capability at its plant in Central Point, Oregon. Erickson Air-Crane can produce “0-hour” aircraft.

5.2.1.6. Maintainability

The S-64F has a maintenance burden that is not unlike other large helicopters. Because of the mechanical complexity, the maintenance requirements for a large helicopter are typically more burdensome than for large fixed-wing aircraft.

5.2.2. Helicopter, SH-60 Variable Stability Seahawk (VSS)

	Spacecraft Lander Development Support	Training Effectiveness	Simulation Fidelity	Safety and Reliability	Cost and Availability	Maintainability
Variable Stability Helicopter	Sensor closed loop testing, pilot interface & visibility	Two Pilots, Pitch cannot be de-coupled from *g* offset	Pitch not de-coupled from *g* offset, Pot. VRS	Mature Development	Lower than Air Crane or Gimbaled Jet	Helicopter

The SH-60 VSS (Variable Stability Seahawk) concept summary is discussed in this section. A more detailed presentation is shown in Appendix F.

5.2.2.1. Spacecraft Lander Development Support

The VSS and the production Seahawk have value for initial exposure and risk reduction, and can be used for primary VTOL training. The SH-60 VSS-type helicopter (e.g., RASCAL) can provide good first-order training, especially in the landing phase.

5.2.2.2. Training Effectiveness

The dual cockpit and inability to decouple the rotor thrust from earth g offset make this vehicle marginal for training effectiveness compared to the Gimbaled Jet and Air Crane. However, as in Apollo, it can provide excellent familiarization training for VTOL operations.

5.2.2.3. Simulation Fidelity

Despite its unique capabilities, a United States Naval Test Pilot School (USNTPS) VSS style architecture is not ideal for a lunar landing trainer. The in flight simulator is capable of producing spacecraft lander body rates in pitch, roll, and yaw within the limited authority of the stability augmentation system (SAS) actuators and achieve analogous first order time constants in each axis. Some correction for attitude/translational acceleration can be made by use of the fly-by-wire (FBW) stabilator, but the correction authority would be somewhat limited and requires some initial incorrect acceleration to put dynamic pressure over the tail first. The VSS was designed as a teaching tool not an experimental/ research tool. The VSS is not intended to simulate any particular helicopter, just a range of sensitivity/damping in the training environment. However, the VSS and even the production Seahawk have value for initial exposure and risk reduction. A Seahawk is a better analogue of an LM than an entry-level training helicopter like the TH-57. The use of a VSS-type architecture would be valuable as a primary exposure to VTOL flying with variable flying qualities in the ballpark and analogous fields-of-view. An ideal system would be a full authority FBW with active control inceptors that could be configured more easily to match those of the spacecraft lander design.

Currently under development is a full authority FBW upgrade to the H-60 Hawk family with a glass cockpit (Figure 12). Rapid risk reduction and development for the UH-60M Upgrade FBW flight control system was recently completed in the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) JUH-60A in in-flight simulator [Ref. 8].

The RASCAL was modified to host elements of the UH-60M upgrade including a prototype active control inceptor system. Active control inceptors like this with the mechanical flight control having been removed would make the UH-60M FBW Upgrade easily reconfigurable to represent potential spacecraft landing trainer crew stations. Additionally the incorporation on an Embedded GPS/INS (EGI) navigation system greatly enhances system performance over that of the Variable Stability Seahawk Architecture. For hover and near-hover operations the JUH-60A used a attitude command/hover hold response type control strategy in the pitch and roll axes, heading rate command with heading hold in the yaw axis, and a vertical speed command/altitude hold in the vertical axis. In this mode, displacement of the active cyclic inceptor from center produced a change in attitude proportional to the amount of inceptor displacement. When the inceptor was placed back to center the aircraft decelerated back to zero velocity as defined by the EGI nav system. Once back in a stable hover the system establishes actual position hold.

Figure 12 MH-60M Blackhawk FBW / CAS Upgrade

This type of control is almost identical to that of the Apollo LM primary hover/landing control. The RASCAL could easily achieve body rates required because the in-flight simulator has 100% control authority. Force/displacement vs. aircraft attitude can be made to be whatever is in the spacecraft lander. A RASCAL-type architecture would have the same concerns with attitude/translational acceleration. More information in the RASCAL can be found in reference 8.

Figure 13 was originally developed in an analysis for the ALHAT research team at Johns Hopkins University Applied Physics Laboratory. The analysis was a feasibility study or the potential use of existing VTOL aircraft as demonstrator platforms for the ALHAT sensor package. The lunar descent trajectories shown represent the current trade space and don't represent hard ALHAT sensor requirements. The bold red line in this chart represents the descent capabilities of a Seahawk helicopter at a nominal gross weight. Starting from the right the curved line represents a steady-state autorotation. Above the autorotation line the helicopter can only descend faster at the expense of over-speeding the rotor system. At low airspeeds, the helicopter can no longer efficiently exchange rate of descent to drive the rotor system and must add engine power. Below 20 KIAS at high rates of descent, helicopters are susceptible to entering a condition called Vortex Ring State (VRS). VRS is a result of the rotor disk ingesting it's own wingtip vortices. All of the engine power goes into recirculation of the rotor tip vortex and the helicopter enters an uncontrolled rate of descent that can exceed 6,000 FPM. The only way to recover from fully developed VRS is to enter an autorotation and fly out of it, which requires at least 1,500 ft. The dashed bold red line represents what a helicopter with higher disk loading like the H-53 achieves. However, any rate-of-descent (ROD)/airspeed combination that puts a VTOL aircraft near VRS is considered very high risk.

The straight green line represents the original Apollo descent concept. In general, the ALHAT trajectories predominately operate in the VRS region, although there are some portions that reside in the normal thrusting region. A helicopter like the Seahawk would be able to do a portion of those profiles outside the VRS region. This chart shows that modern VTOL aircraft are still limited to being able to simulate lunar descent and landing at lower altitudes and lower rates of descent. This is a limitation also shared with the Apollo-era LLTV.

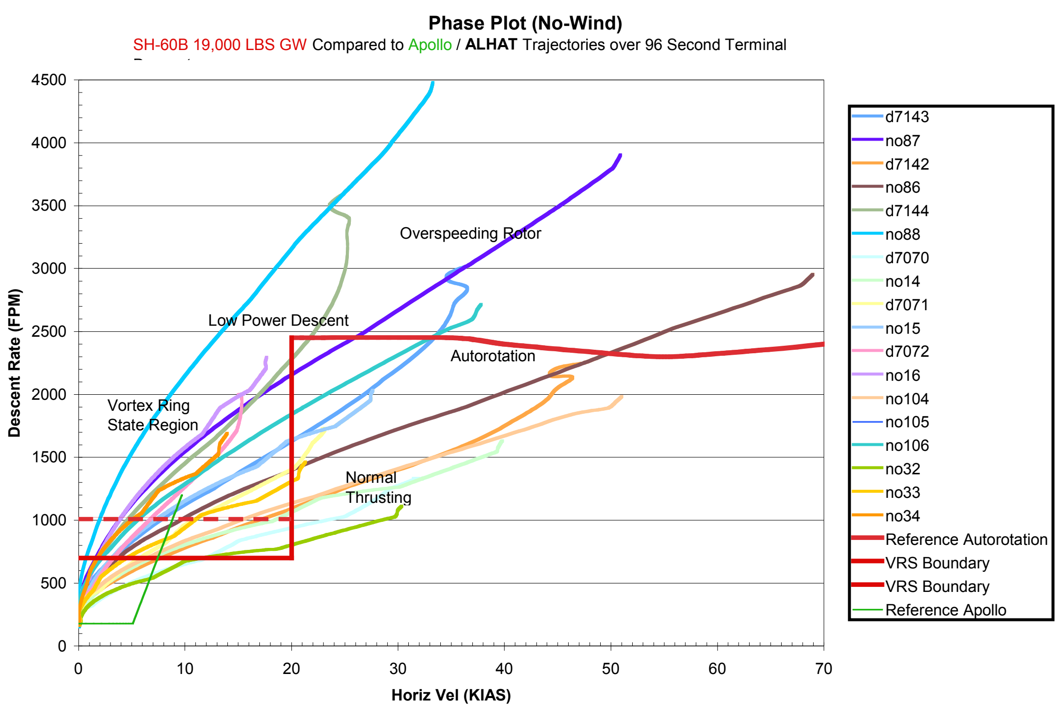

Figure 13 ALHAT Trajectories Compared to Helicopter Descent Capabilities

5.2.2.4. Safety and Reliability

The US Navy Test Pilot School (USNTPS) has an extraordinary record of risk management in VSS operations. The school has been safely demonstrating VTOL variable flying qualities in a training environment for over 15 years. The Commander of Naval Test Wing Atlantic granted USNTPS a waiver for non-pilot flight test engineers (FTEs) to fly VSS syllabus flights based on an extensive risk analysis and history of safe operations. Normally these engineers are forbidden from touching the controls below 200 ft AGL or flying during "critical phase of flight." The risk of allowing the FTE to operate the controls in VSS syllabus flights is mitigated by:

- Limiting FTE events to instructor pilots (IPs) with more than 25 VSS instructional hours
- Flying at no lower than 20ft AGL.
- Progressing through a known series of configurations that are proportionally spaced.
- Using a defined buildup path through the demonstration points starting with analogues of syllabus aircraft.
- The VSS interface allows the IP to sequentially cycle through configurations with hands on controls.
- Automatic safety trips and manual VSS secure switches are on the controls

Within the confines of the current test plan, the VSS is not allowed to touch down with the VSS computer engaged. However, the H-60 radar altimeter is about 5 ft below the pilot design eye position so a 20 ft hover on the radar altimeter is about 15 ft height-of-eye. The Apollo LM height-of-eye on touchdown was about 16ft. Therefore, a 20 ft hover represents a virtual touchdown with similar cues. If non-pilot FTEs can be safely trained in an aircraft like the VSS, then certainly astronauts can be. A summary of the Variable Stability Seahawk risks are shown in Figure 14.

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- VSS
  - Safety Pilot Onboard
  - Two Engines
  - Complete production control system available in parallel
  - Exists and is being actively and safely used in a training environment NOW
  - Could possibly be partially modified within existing programs and contracts
  - Can only really simulate the last 200ft-500ft of the descent
  - Mishap rate over 15 years – 0%

Figure 14 Variable Stability Seahawk Risk Summary

5.2.2.5. Cost and Availability

To estimate costs of a model following partial authority FBW system like the Seahawk VSS using an analogy cost-estimating method.

1) The implementation of VSS-I to VSS-II was a fist order increase in capability
2) VSS-I cost $1.2M corrected to 2008
3) VSS-II cost 2.2M corrected to 2008
4) That is almost a doubling in cost (rounding up).
5) Estimating that a hypothetical VSS-III (assuming an acceptable solution to the LLTV requirements could be met) would be a second order increase in capability and result in a fourfold increase in development cost over VSS-I for approximately $4.8 M rounded up to $5M (2008).

The system would be set up in a current production Seahawk, most likely an MH-60S. The MH-60S cost is approximately $19M (2008) based on the current negotiated contract price based on the entire Navy program buy. The VSS-II implementation as is currently configured would be about $2.2M (2008). That would put the cost of a single MH-60S based VSS-III at about $24M (2008). This analysis did not account for a cockpit conversion to a 100% LLTV pilot-vehicle interface with active control inceptors. For comparison, the RASCAL upgrade cost $22M in 1990 dollars projected to $37M 2008 dollars.

The H-60 Hawk family of helicopters is the core helicopter capability in both the U.S. Army and U.S. Navy and will continue to be so for the next thirty years. It is expected that extensive support will be available throughout that lifecycle.

5.2.2.6. Maintainability

There are general inspections, calendar/special inspections, and flight hour based inspections for the SH-60. Most have windows during which they can be accomplished. Though undesirable, most inspections can be re-based if required by operational considerations. Non-compliance with any inspection is a downing discrepancy without a Commander of Naval Air Forces Atlantic/Pacific (CNAL) extension. Unscheduled maintenance is performed on an as required basis and preventive maintenance is continuous. The inspection schedule, although more frequent than a typical fixed-wing aircraft, will allow the SH-60 to maintain the anticipated flight requirements of a trainer platform.

5.3. VTOL / STOVL

Vertical Take-Off and Landing (VTOL) refers to a class of aircraft that can take off and land vertically. Short takeoff and vertical landing (STOVL) refers to a class of aircraft that takeoff from a short runway and land vertically. Aircraft of these classes include the AV8-B Harrier, the F-35B Lightning II, the V-22 Osprey, and numerous others. Vertical lift can be produced through the use of diverted turbofan thrust, direct lift-fans, or propellers. Traditionally, these aircraft were designed to operate within the vertical flight regime only as a means of transitioning to and from forward flight. As a result, performance and safety within these regions often suffered, and pilot workload was very high. Advances in engine performance and flight control systems have brought a much-improved level of stability and automation to the vertical flight mode of the F-35B and V-22. Two VTOL concepts were considered for this study.

5.3.1. V-22 Osprey / Tilt-Rotor

	Spacecraft Lander Development Support	Training Effectiveness	Simulation Fidelity	Safety and Reliability	Cost and Availability	Maintainability
V-22 Osprey Tilt Rotor		**Too many deficiencies**				

The V-22 Osprey is a tilt-rotor Vertical Takeoff and Landing (VTOL) aircraft. Its twin rotors are oriented vertically for takeoff, landing, and vertical flight. The nacelles can be rotated 90° forward to transition from vertical flight to forward flight, at which point primary lift is provided by a conventional wing and the rotors provide forward propulsive thrust.

5.3.1.1.Spacecraft Lander Development Support

The V-22 was designed to carry both internal loads and external slung loads. If it were necessary to add additional equipment for research purposes, it would be capable of carrying anything necessary to accomplish this task. Since the body of the V-22 does not gimbal in multiple axes, and since the attitude is controlled using the nacelles and conventional helicopter swashplates instead of RCS, it is unlikely that the V-22 would be a good research platform for these components.

5.3.1.2. Training Effectiveness

The aerodynamic response and lack of roll decoupling of the earth g offset makes this vehicle unsuitable for the mission.

5.3.1.3. Simulation Fidelity

The V-22 is capable of meeting some of the performance and design metrics of the Free-flight Simulator training task, but falls short in several respects. Figure 15 shows the LDAC and ALHAT approach phase trajectories plotted against the high sink rate limits as specified in the V-22 NATOPS (A1-V22AB-NFM-000). If the sink rate falls below the thick red line, the aircraft will very likely enter the vortex ring state. Out of the 14 trajectories, six fall within the vortex ring state region. If any of these six trajectories were to be flown, the initial part of each trajectory would have to be truncated to remain outside the high sink rate region. During the landing phase, all trajectories fall outside of the high sink rate region.

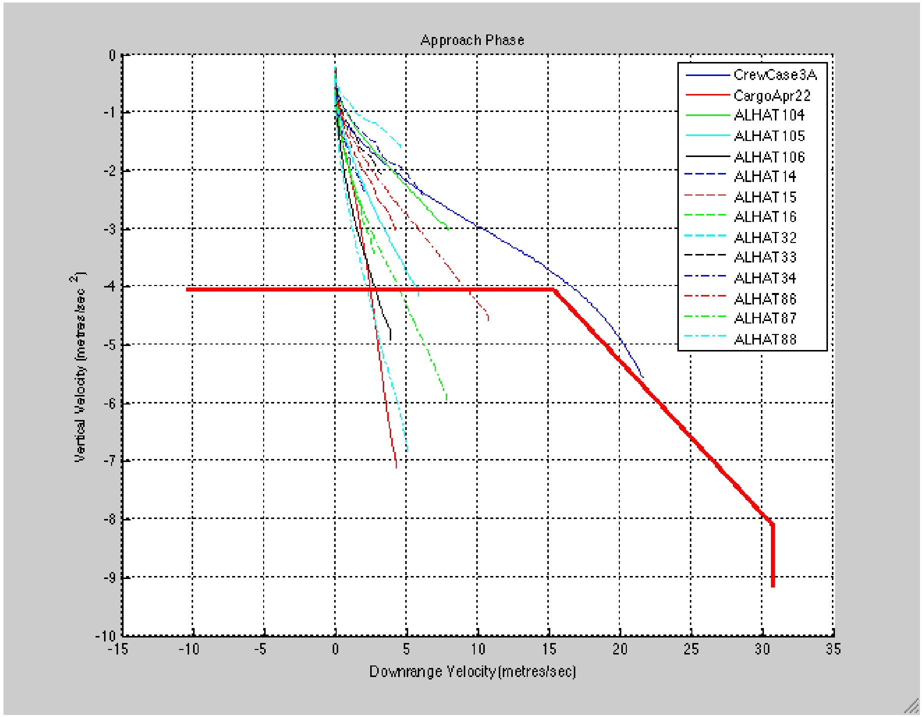

Figure 15 LDAC and ALHAT Approach Trajectories and Vortex Ring State Region

In order to provide for an accurate training environment, the Free-flight Simulator must simulate the performance and flight characteristics of the spacecraft lander. One such requirement is the ability for the Free-flight Simulator to pitch and roll up to 40° to simulate the anticipated attitude range of the spacecraft lander. In doing so, the Free-flight Simulator must match the angular response as well as the translational response of the spacecraft lander. The ability of the V-22 to rotate the engine nacelles suggested the possibility of decoupling the pitch attitude from the translational response to properly simulate the spacecraft lander dynamics. To implement such a system, the flight control laws would have to be modified, and pitch rates would be limited to less than the nacelle rotation rate of 8 deg/sec.

Theoretical range of pitch attitude would be from 7.5° nose-down to 40° nose-up. Roll decoupling is not possible and, if the Free-flight Simulator were at a non-zero pitch attitude, rolling motion would result in rolling about the local vertical and not the simulated spacecraft lander body axis. Similarly, the yaw axis is free to rotate to any angle; however, a non-zero pitch attitude would result in an inaccurate yawing motion about the local vertical rather than the simulated spacecraft lander body axis.

The mass of an Free-flight Simulator configured V-22 is approximately 60% of the LDAC-2 spacecraft lander mass, which would improve the chances of the V-22 Free-flight Simulator being capable of matching the Altair spacecraft lander dynamics; however, performance data for the V-22 has yet to be obtained for this comparison.

The V-22 is capable of flying in headwinds up to 45kts and crosswinds of up to 20kts. It should be able to compensate for steady winds up to these values, but it is likely that gusts would have some effect on the fidelity of the simulation.

In order to match the field of view of the V-22 Free-flight Simulator to that of the spacecraft lander, the cockpit windows would need to be masked. Additional external masking could be added to simulate the obstruction of view by the upper deck of the spacecraft lander. To simulate the level above the ground on touchdown, a technique similar to that of the STA operations would be used, in which the ground level would be simulated, and the V-22 would not actually touch down on each simulated landing. Due to the limited cabin size, the astronaut will likely be in a seated position rather than standing. As a result, the astronaut's head will potentially be further away from the window than in the spacecraft lander, changing the visual picture. Additionally, the positioning of the astronaut's head will be between 5m (15ft) and 7m (20ft) ahead of the center of gravity (CG), and close to the vertical position. The position of the astronaut's head from the spacecraft lander CG is roughly 3m (10ft) above, and 1m (3ft) ahead of the CG. Thus, the motion cueing would not be accurate on the V-22 Free-flight Simulator. It is likely that the cockpit layout could be made to be very similar to the spacecraft lander cockpit. It might also be possible to reconfigure the trainee so that they are standing crouched in the cockpit, partially simulating the spacecraft lander crew positioning.

5.3.1.4. Safety and Reliability

There have been four V-22 crashes as of the writing of this document. The first was lost due to a miswired flight control system, while the second was due to a gearbox leak and subsequent fire in an engine pod. The third was due to the aircraft entering into the Vortex Ring State (VRS), and the fourth was due to a hydraulic leak. It is assumed that in time, the mechanical failures can be eventually remedied. On the other hand, the VRS incident was due to an operational error, which has since been mitigated. After the V-22 was lost due to entering the VRS, a flight program was performed to determine the VRS region for the V-22, as well as to develop a procedure for escaping from this flight condition should it be encountered. As a result of this program, a warning system monitors descent rate and airspeed and provides an audible warning to the pilot if the aircraft is approaching the VRS state. If VRS is encountered, the mitigating action is for the pilot to angle the nacelles forward slightly, building airspeed and escaping the VRS condition. The V-22 has been designed with the typical redundancy found in military aircraft including, among other things, triple redundant flight computers, triple redundant hydraulic systems, and a driveshaft connecting the two rotors so that both may be driven by a single engine should an engine failure occur during flight. The V-22, configured as a Free-flight Simulator, would not contain any hazardous materials beyond those required for standard V-22 operations. A safety pilot would be available, and would pilot the V-22 to the initial conditions for the landing task as well as take control of the vehicle if envelope limits are exceeded.

5.3.1.5. Cost and Availability

Not Available, likely to be prohibitive.

5.3.1.6. Maintainability

A V-22 modified as an Free-flight Simulator would not require any special facilities. Maintenance burden and inspection schedules information still need to be collected. The complexity of flight inspections would not be much more extensive than for regular V-22 operations.

5.3.2. AV-8B Harrier

	Spacecraft Lander Development Support	Training Effectiveness	Simulation Fidelity	Safety and Reliability	Cost and Availability	Maintainability
AV- 8B Harrier VTOL		Too many deficiencies			Availability in question	

5.3.2.1. Spacecraft Lander Development Support

The Harrier is very limited in payload during jet-borne (hover) flight. Therefore, the flexibility ranking is red.

5.3.2.2. Training Effectiveness

Too many deficiencies.

5.3.2.3. Simulation Fidelity

The AV-8B Harrier can hover for approximately 20-25 minutes. The duration is limited by the weight of the fuel that can be lifted in vertical take-off and the density altitude. A LLTV simulation requires the lunar gravity offset always to be in the vertical plane. The Harrier has the capability to turn the thrust nozzles 90 degrees aft and 8 degrees forward manually. Possibly this system could be modified to provide ± 49 degrees of travel in the pitch plane only. This alone limits a Harrier based LLTV to a pitch only simulator. Therefore the following discussion will only include pitch performance.

The Harrier is capable of flying both approach and landing phases altitudes, down range distances, and horizontal velocities. The approach phase vertical velocity would have to be limited to 4.3 m/s (850 fpm) using the Harrier. The attitude, rotational rates, and rotational accelerations are less than required due to the limited RCS authority. Normal hover pitch attitudes should be between 3 and 12 degrees nose high, most likely to reduce the risk of losing control.

An automated control system would need to be developed to turn the exhaust nozzles and adjust throttle to maintain the gravity offset and balance (remove aerodynamic forces).

The field of view and cockpit layout would match best if a Harrier nose were grafted onto the spacecraft lander. Otherwise, the Harrier will require extensive modifications or replacement of the nose with careful attention given to blockage of the engine intake.

Due to the limitations mentioned in this section the Harrier was rated red for simulation fidelity.

5.3.2.4. Safety and Reliability

Crew survivability is provided by ejection seats and long travel landing gear. Cockpit modifications could compromise the use of the ejection seats. Ejections need to be initiated before extreme attitudes or high sink rates are encountered.

Initial Harrier loss rates were high at 39 accidents per 100,000 flight hours. Through modifications to the aircraft and operational procedures the loss rate was reduced to 12.1.

National Transportation Safety Board (NTSB) reports show General Aviation had improving accident rates less than 12.1 since 1978. Even amateur built aircraft accident rates are lower. Using the Harrier outside the envelope will increase the chances for a mishap.

The RCS control system on the Harrier is adequate for maintaining a level attitude in hover and transitioning to forward flight. A crosswind or sideslip exceeding 10 knots can result in a rolling moment that exceeds the authority of the RCS system. High rotational rates or accelerations also can exceed the authority of the RCS system. Large inputs on more than one axis will overtax the RCS system.

Hazardous modes include the previously mentioned sideslip, high rotations, hot gas ingestion near the ground, and upsets due to engine exhaust being deflected from the ground and impinging on wings. High descent rates can cause loss of control. A large uncontrollable nose down pitching moment is produced if the aft nozzles impinge on the wings flaps. Most off these modes are unrecoverable at low altitude.

The two seat training version of the Harrier could have provisions for a safety/simulation pilot. The two seat versions and second occupant will reduce the duration of flight due to reduction of initial fuel load.

The Harrier was ranked yellow for safety and reliability due to the poor accident rate.

5.3.2.5. Cost and Availability

The reduction of the fleet should make acquisition of single seat versions easier. However, only six two seat training versions were produced and will remain in service.

Modifications to perform lunar simulations will be extensive. Verification and validation of the modifications will be on the order of a scratch built vehicle.

The Harrier is ranked red for cost and availability due to the expense of modification and lack of numbers of two seat versions. The ranking is unlikely to change if the final training method does not require a safety pilot (can use single seat versions).

5.3.2.6. Maintainability

Maintenance is on the order of most other military aircraft of this size. The Harrier is being phased out of service in favor of the JSF. Eventually, spare parts will need to be acquired from retired airframes. The Harrier was ranked yellow for maintainability because it will be an orphaned airframe.

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