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PILOT SAFETY FOR THE X-24A LIFTING BODY VEHICLE

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INTRODUCTION

The X-24A is a manned lifting body flight vehicle, engaged in a flight research program at Edwards Air Force Base, California. The aerodynamic configuration of the X-24A was developed by the Martin Marietta Corporation over a period of years in connection with in-house studies and Air Force contracts. The final configuration evolving from these studies was identified as the SV-5. The SV-5 configuration featured medium hypersonic lift to drag ratios, good subsonic performance, and a high volumetric efficiency.

Three small scale SV-5D vehicles, identified as the PRIME, were fabricated by Martin under Air Force contract. They successfully demonstrated flight from entry into the earth's atmosphere at orbital speeds down to 100,000 feet altitude at a velocity of Mach 2.0. The unmanned PRIME vehicles were approximately one fourth the size of the X-24A and weighed approximately 800 pounds. Recovery was by "air snatch" following deployment of a ballute and a parachute.

DESIGN AND OPERATIONAL CHARACTERISTICS

The X-24A is approximately 24 feet long, weighs approximately 5500 pounds empty, and has an internal tankage capacity for approximately 5500 pounds of propellants and gases. It is of conventional aluminum alloy construction and is powered by the XLR-11 rocket engine developed over twenty years ago. The main propellants are liquid oxygen and alcohol. Hydrogen peroxide is used to power the turbopump and helium is used to pressurize the tanks and actuate the valves. The vacuum thrust of the engine is approximately 8500 pounds and the maximum burn time at full thrust is nominally 140 seconds. 500 pound thrust hydrogen peroxide fueled rocket engines are also provided for use as "landing engines".

Control of the X-24A is by means of 8 movable aerodynamic surfaces. These surfaces are powered by a duel redundant hydraulic system and respond to either pilot commands or the inputs from a triple redundant stability augmentation system. Various modes of control are possible with the X-24A and the development of a "control law" has been one of the objectives of the flight research program. Generally the upper flaps are "biased" to the open position at high speeds (minus 40 degrees above 0.60 Mach number, for example) and are closed up at low speeds and for landing. The pilot has the capability, however, to open them up for use as speed brakes. Usually, pitch control is accomplished by simultaneous deflection of the lower flaps while roll control results from differential deflection. When the upper flaps are "closed up", some of the pitch and roll control functions are transferred to them at which time they act in concert with the lower flaps.

The upper and lower rudders on each side may be moved together in response to "bias" signals and are generally toed-in 10 degrees for low speeds and toed-out 2 degrees for high speeds. The upper rudders on each side move together in response to the pilots commands, inputs from the stability augmentation, and in response to commands from a rudder-aileron interconnect system. The rudder-aileron interconnect system deflects the rudders in proportion to aileron deflection to counteract the adverse yaw which results from aileron deflection. Aileron action is, of course, obtained by differential deflection of the flaps as explained above.

The normal mode of operation of the X-24A is to launch the vehicle from a B-52 mother ship at approximately 45,000 feet and a Mach number of 0.69. Early flights were made in a strictly glide mode. Later, the XLR-11 rocket engine was started after launch and the X-24A was climbed to altitudes in excess of 70,000 feet and accelerated to velocities in excess of Mach 1.60. In all cases, however, the final portion of the flight consists of an unpowered glide to a conventional airplane type landing on the dry lake at Edwards Air Force Base.

SAFETY CONSIDERATIONS FOR VEHICLE DESIGN

The "one of a kind" research mission of the X-24A dictated that great emphasis be placed on safety during the design of the X-24A. Initial criteria were developed on the basis of experience with other resear[illegible] flight vehicles such as the X-15 and on the [illegible]sis of the predicted flight characteristics of the X-24A.

The inherently high drag of the lifting body configuration together with its relatively low lift/drag ratio (typically 2.0 to 4.4), generated considerable concern with respect to the pilot's ability to perform safe landings from gliding flight. Accordingly, the "landing engines" were incorporated into the design to provide an increase in the apparent lift/drag ratio during flare and landing. Experience with the X-24A has since shown that this concern was not warranted. The landing rockets were used on the first three flights, but have not been used on the following twenty-two flights.

In the early stages of design, all systems were reviewed for critical areas. A failure mode and effects analysis was performed. Redundancy and other techniques were used to insure safe operation to touchdown and roll out after one or more component failures occurred.

Start failure of the XLR-11 engine would require immediate jettisoning of the main propellant. Therefore, a bypass system was designed which would route helium directly from the storage tank to the main propellant tanks. An interlock with the jettison valves prevented opening of the bypass system unless the jettison valves were open. Thus, a failure of the normal pressure regulating system in the closed mode would not preclude jettisoning of the main propellants.

The hydrogen peroxide tank is pressurized with helium to 475 psia. The helium is stored at 4200 psia and routed through a pressure regulator to achieve the desired pressure drop. An open failure of the regulator would over pressurize the peroxide tank and cause a catastrophic failure. This single point failure was eliminated by incorporation of a dual redundant relief valve in the peroxide tank. Depletion of the helium source through the vent is prevented by installation of a normally open solenoid valve in series with the regulator. This valve is controlled by a pressure switch, set to a higher pressure than the regulator pressure, but a lower value than the settings on the peroxide tank relief valves. A cockpit switch allows the pilot to close this valve manually if his pressure indications should show a trend to over pressure, or to de-energize the valve if a pressure switch malfunction should cause it to close unnecessarily.

Redundancy techniques were used in the flight control system to eliminate single point catastrophic failure modes. Two independent hydraulic systems are used. Each system is powered by two electric motor driven hydraulic pumps, and each pair of pumps is powered by its own independent battery. In the event of a failure of either of the batteries powering the hydraulic pumps, power is switched to the flight test instrumentation battery, thus providing an additional backup for this mode. The stability augmentation system was made triple redundant to insure that it would always be available to provide its augmentation function, but could not command a "hard-over" or other erroneous control signal. Each axis of the system has three parallel rate gyros, associated electronics, and a logic circuit which insures that a malfunction in one of the three parallel channels will not cause a hardover or disable the system.

The X-24A flight control system consists of a relatively complex mechanical linkage which accomplishes the required mixing and crossover functions in order to transfer the command signals from the pilot and the stability augmentation system to the flaps and rudders.

In order to thoroughly evaluate the operation of the flight control system under normal and malfunction conditions and to accomplish the necessary development work in an orderly and expeditious manner, the entire system was assembled on a structural steel mockup for fixed-base closed loop simulation. All attachment points to the basic X-24A structure were duplicated by the structural steel frame work. The hydraulic power actuators moved dummy control surfaces which were loaded in a manner to simulate airloads. This was accomplished with air cylinders pressurized from a regulated source of compressed gas. Control surfaces position was measured with potentiometers and the electrical signal was fed into an analog computer. A complete set of pilot flight controls was provided and the position of these controls was also fed into the computer. The motions of the X-24A which would have resulted from the various control positions was calculated by the computer and displayed on the pilot's flight instruments (attitude indicator, Machmeter, altimeter, etc) and also recorded on strip charts for engineering analysis.

Experienced pilots "flew" numerous missions in both normal and malfunction modes. These tests provided functional verification of overall system operation and permitted an assessment of the pilot's ability to use the manual backup controls to correct system malfunctions. A typical example would be a failure in the automatic flap bias system tending to drive the upper flaps to an extreme position. The pilot was able to switch to the manual mode and "beep" the flap to the desired position before the development of a serious situation.

After delivery of the X-24A to the government, gull scale wind tunnel tests were run in the large low speed tunnel at the Ames Research Center. Additional small scale tests were run, and this data together with the measured characteristics of the actual X-24A flight control system were used to develop an accurate simulation program. This simulation did not include the actual flight control systems hardware as in the flight controls test stand described above. Instead the measured characteristics of the flight control system were programmed into the computer. This simulator provided an accurate duplication of the cockpit controls and displays and the computer output drove both the pilot's displays and an X-Y plotter similar to the one used to control actual flights.

OPERATIONAL SAFETY

Flight planning for the X-24A starts with a review of all available data from preceding flights and a comparison of this data with wind tunnel results. A configuration (control settings, gains, etc) is established for the flight together with a set of flight objectives. In general, the flight objectives are to obtain specific data under certain flight conditions (Mach number, angle of attack, etc). Flight planning for a vehicle such as the X-24A must consider many factors in attempting to accomplish the desired flight objectives. Energy must be programmed to insure that the primary landing site will be reached with sufficient speed and altitude to insure a safe landing, but provisions must also be made for abnormal situations such as an early engine shutdown. The simulator is used as a tool for planning the nominal trajectory as well as all malfunction situations. In addition, it is used as a means of evaluating changes to the flight control system or other ships systems relative to their effect on stability and control and performance.

Once a satisfactory flight plan has been developed, the simulator is used for crew training. The general procedure used in the lifting body flight test program has been to have at least two pilots specifically assigned to one of the flight vehicles and at least three pilots active in the program. One of the X-24A pilots is assigned to fly the mission and the other pilot is assigned as the controller (NASA One). Usually, the third pilot, although not specifically assigned to the X-24A, will fly chase. The flight planner, the controller (NASA One), and the mission pilot use the simulator to train for the mission as a team.

As a further training aid, F-104 aircraft are used as airborne simulators for the approach and landing phases of the mission. Aerodynamic data for the X-24A and for the F-104 are utilized to establish an F-104 configuration which will give it lift/drag ratios comparable to that anticipated for the X-24A in the upcoming mission. Typically, the F-104 is flown with gear and flaps down, speed brakes extended, and engine at minimal power settings to duplicate the low lift/drag ratio of the lifting body. Practice approaches are flown for the normal mission and for all of the malfunction cases. On the morning before the flight, a final set of practice approaches are flown, usually with the chase pilot accompanying. Thus, when the mission pilot embarks on the actual X-24A mission, all normal and emergency aspects of the mission have been experienced and he is thoroughly prepared for any foreseeable situation which might develop.

A further safety procedure followed in the development of an X-24A mission involves preparation of the formal written flight plan, and the technical and crew briefings. The flight plan spells out in detail all aspects of the flight. Each event in the flight is detailed in terms of Mach number, altitude, angle of attack, elapsed time, and maneuver to be accomplished. A set of ground rules for "no launch" and a set of alternate situations after launch are defined in detail.

Several days before the scheduled day, a technical briefing is held. This briefing is attended by all cognizant personnel from both NASA Flight Research Center and the Air Force Flight Test Center. Data from the preceding flight are reviewed and the technical aspects of the upcoming flight are discussed in detail. Finally, the written flight plan is reviewed. All questions raised at this briefing are answered satisfactorily as a prerequisite of the flight.

The crew briefing is accomplished during the afternoon preceding the scheduled flight day. This briefing is attended by all personnel who will participate in the actual accomplishment of the flight. All operational aspects are reviewed and the personnel assigned to accomplish specific tasks are identified. Any special operating procedures are discussed and the chase pilots, B-52 mother ship pilots, airborne photographers, and mission pilot coordinate their activities at this time.

Servicing of the X-24A begins approximately two hours prior to pilot entry into the cockpit. A complete controls system check is accomplished during this time period. "Throw-boards" are attached to the X-24A to measure control surface deflections. An observer is stationed in a position to make the desired readings. The crew chief operates the controls in the X-24A cockpit and a controls engineer directs the test from the control room. The X-24A telemetry system is operative and driving the strip recorders which display control positions in the control room. All personnel participating in the test are in radio and/or telephone communication. The test verifies that the control surfaces are in fact properly responding to the pilots cockpit control motions and that the control room recorders are displaying the actual positions of the control surfaces. This check also verifies proper operation of the stability augmentation system and the automatic bias system.

Approximately 30 minutes prior to pilot cockpit entry, the pilot is prepared for flight. A special van located near the X-24A is utilized to instrument the pilot and fit him into his full pressure suit. Since powered flights of the X-24A are normally made to altitudes in excess of 50,000 feet, the pilot wears a full pressure suit as a backup in the event of cabin pressurization failure. In order to obtain biomedical data, the pilot is instrumented with special sensors, the output of which are recorded on a small tape recorder. A flight surgeon is present during all preparation of the pilot for flight to provide medical aid in the event of an accident, and to observe the pilot for any signs of distress. This procedure was instituted when a lifting body pilot suffered severe dehydration due to the high ambient temperatures (Edwards Air Force Base in the summer) encountered during a hold which occurred after cockpit entry.

After pilot entry into the cockpit, the X-24A crew chief and the chief inspector go over the "pilot entry checklist" with the pilot to verify the position of all cockpit controls and the reading of the appropriate displays. The entire captive portion of the flight is also conducted in accordance with a carefully prepared checklist i.e. countdown.

Timing of the checklist during captive flight is a function of B-52 position and is arranged so that completion of the checklist occurs just as the B-52 approaches the launch point. During the captive portion of the flight, another complete controls system check is accomplished. This check verifies proper operation of the system in the actual flight environment. In addition, pitch and yaw pulses of the B-52 permit an operational check of the stability augmentation system. Air for cabin pressurization, breathing oxygen, and electric power for the X-24A are provided from the B-52 until approximately five minutes before launch. At that time a switchover is made to internal systems and a check is made to determine that operation is satisfactory.

Upon reaching the launch point, the pilot launches himself and proceeds with the flight according to plan. The flight is monitored from the ground and all communications with the pilot are filtered through the controller (NASA One). The pilot is advised of any malfunction or abnormality and provided with recommended corrective action. His trajectory is monitored from the radar driven X-Y plot and heading and climb angle corrections are provided as required. During the approach, the chase pilot flies in close proximity to the

X-24A and provides airspeed, altitude, and turbulence information. In addition, the chase pilot verifies satisfactory extension of the landing gear and advises the pilot of his height above the runway during the last 100 feet of descent. Normally, the chase aircraft touches down in formation with the X-24A. The entire operation is one in which teamwork and thorough training play a very important part. By means of these procedures, flight testing of advanced, radically configured experimental flight vehicles is conducted in a very safe manner on an almost routine basis.

CONCLUSION

The lifting body flight test program has been conducted on an extremely austere basis. The entire cost to the government of the X-24A program, including vehicle acquisition, has been less than the cost of many paper studies. Yet, there has been no compromise with safety. Safe operation of such a radical flight vehicle has required careful attention to safety considerations from the beginning of the design process, and with continued emphasis right through the flight program.

SESSION II

QUESTIONS AND ANSWERS

QUESTION: John, where do we go from here in manned lifting bodies? Is the space shuttle next or is there something in between?

MR. COCHRANE: The present plan is to modify the X-24A to a new configuration known as the X-24B which has higher hypersonic performance. It will be a sort of long skinny vehicle instead of a short fat one but it is the same basic core. We will actually add the structure to this vehicle and retain the systems, that is anticipated to be done sometime late this year. Then, a lot of us at NASA are hoping that we will have a similar type vehicle to represent one of the space shuttle orbiters or boosters perhaps. I think the booster is the one that they are thinking of presently.

QUESTION: What is the thrust in the "B"?

MR. COCHRANE: It will be the same thrust. The engine will be the same and the engine does develop 8500 lbs. of vacuum thrust.

COMMENT: You mean the engine is still good, we are going to use it many more years, right John?

MR. COCHRANE: Yes sir, I might comment that the present thinking is to use two of them. This would give us eight chambers in the drop vehicles, that is the shuttle vehicle--space scale shuttle, and I shutter to think of getting eight of them going. Yesterday we sure had a lot of trouble getting four going.

QUESTION: Did you use any techniques of system safety discipline on the X-24A or did you just design in good safety features.

MR. COCHRANE: I would say yes, but I have to qualify it. I deliberately did not get into a discussion of it because I didn't have time. I think what it was, the technical director on our program had been a reliability engineer previously and the techniques were not the formal techniques that have been discussed here earlier, that is with charts and procedures, etc., but it was a case of, I think individual responsibility, people who had worked in the area and who were very aware of it. I don't know if that answers your questions.

MR. GORDON SMITH/A.F. SYSTEMS COMMAND: Mr. Hammer -- Willie, I know you made a number of comments about changes that are needed in MIL-STD-882. I was wondering whether you have already submitted these officially for consideration or whether you are going to submit them?

MR. HAMMER: No I haven't submitted them officially at all. As a matter of fact, it was only Thursday or Friday that I heard the Air Force was actually thinking of revising MIL-STD-882. Lets say I presented a few comments, I even have a few that I did not put up here because I didn't think that they were that important. If you want Gordon, I can just get you a copy and hand them to you.

MR. SMITH: The best thing Willie is to submit them on that form that is in the back of the MIL-STD. When we went through the last exercise we got recommended changes on wrapping paper and everything else and we had one heck of a time. We are hoping in this current revision of 882 to stick to the format of the form that is in the back of each copy of the MIL-STD, then we have them in apple-pie order and we can give them due consideration. There is one other advantage of using that form, with the high postage rates, the way they are, we pay the postage on that form.

QUESTION: Mr. Hammer you made a couple of statements on MIL-STD-882. One that you would prefer not to see a categorization. As a nuclear system analyst, I'd like to know, when we do analysis what could we use to categorize?

MR. HAMMER: Why do we need categorization. This is what I want to point out, that if the procuring activity or the agency that is interested in getting a system developed actually indicates where the investigations, which way the safety activities should go, you really don't need these safety categories. Actually, the old idea about the categories was the fact that if they said, well if you have a Category IV then you know it is more important than Category III, II, or I. This was the benefit of the four categories. As I say, I think that we have advanced so far now that we really don't need the categories, that whoever is responsible for obtaining a new system could actually stipulate the various problems that they want investigated. In some of the work that I have done with various organization, I found it is a great deal of trouble trying to decide which of the categories these things go into. For example, lets point out this deal about injuries. You have two categories for injury, Category III and Category IV and it is quite a problem trying to determine, if the person who is going to over here going to be subjected to a Category III hazard or is he liable to be killed and be in a Category IV hazard. So as I say then, other things are these delineations between the categories. For example, Category IV talks about system loss; Category III talks about the fact that you might lose the system unless immediate corrective action is taken. Which means that you have a potential for system loss in the Category III hazard, so which do you put it under, Category III and IV. The other point is that we sometimes get the question do you put somethings in Category I, II, III or IV depending on something like the probabilities that Mr. Allison had. Whether it is highly improbable, very low probability of hazard, or do you take anything of any probability and put it in a category and just leave it there?

VOICE: I understand your point but the other one I think we are all interested in, is why is it 180^{o} out of phase with the reliability category.

MR. HAMMER: I hate to say this but I believe that when 38.30 was developed the military specification at that time had four reliability categories. I think they figured if reliability had categories, safety ought to have categories and just to differentiate the two they ran them in opposite directions.

VOICE: Since the speaker asked a question why categories, I guess some of the audience can answer the question. I think the categories were just a stepping stone to management action. For instance in configuration management you'll have a Level I review board, Level II Board, Level III - and when you assign a design change it establishes the level which review and decision can be made. I think there was an implication that Category IV would have to be reviewed as a high level of management; Category III as a low level of management, etc. Unless the management system goes on and says that unless the management system identifies some correlation between the responsibility and authority for disposing of the hazard, then the Category itself is meaningless.

MR. HAMMER: Categories have this one basic advantage, the fact that supposedly you look at the Category IV and you say, we want to pay more attention to that, but we get involved with another problem in determining the categories. For example, taking a missile that we are trying to establish categories on.

Say this is an air launch missile. We know that if the electrical system fails on a missile that has been launched that you have system loss. System loss is Category IV. Now, you can have an electrical system failure for a number of reasons. One of the reasons is that you lose the battery which means that if the battery fails then you have a Category IV hazard. As you go down you begin to analyze what could cause the problems within the batteries and you can have sixteen different items such as touching plates, a poor connection, poor soddering, each one of these things. Does that mean that poor soddering within the battery is a Category IV hazard because you are ultimately going to lose the system. Now you have to have a Philadelphia lawyer to begin to figure out where do you stop categorizing these things as Category IV or Category III. This is not well-defined in MIL-STD 882.

QUESTION: Again for Mr. Hammer, the point of categorization. The categorizing system sure is simply a means of shorthand, I agree that it has serious problems. Perhaps it needs expansion rather than eradication. For example one serious injury or a thousand deaths would both be a Category IV hazard when you can hardly compare the two in any system safety program. That is simply an aside. My question really is that MIL-STD-882 says in about 5900 words exactly what 38-130A said in 2500 words. Is it your opinion that 882 is a step forward? a step backward? or a step sideways in comparison to 38-130?

MR. HAMMER: I think the chief advantage in MIL-STD-882 was in the delineation of the tasks and the various phases. Here again, I think certain of these items should be improved. For example this deal about the system safety program plan, both in 38-139 and MIL-STD-882. In the conceptual phase they have no requirement for the system safety program plan. The system safety program plan actually comes into being in the Phase A definition. I know that lately they started changing the various phases, but it comes into the Phase A definition and it is actually prepared at that time for use during the Phase B and for the engineering phase which means that the system safety program plan according to 882 is not prepared for use during the current work being done on a system. In actuality most of the procuring activities require that a system program plan be prepared and that is actually used during the current phase but it isn't what this says in MIL-STD-882. As I say the big advantage, to answer your question of 882 over 38-130 was the delineation of the safety tasks.

MR. RUSSELL (GE): I have been spending about the last two years working with a chemical and petroleum industry and applying some of these techniques and I would just like to pass on for the benefit of this conference that they continually remind me that a lot of industries are not like NASA and aerospace in terms of dollar resources. Unless I can show them a series of category definitions by which they can decide who can work on these problems and how many dollars that the line manager, as Mr. Pope so adequately pointed out, can be allowed to address this problem with, they are not very much interested in using NASA and Aerospace techniques in their current dilemma with the environment.

MR. HAMMER: I point out the fact that one of the biggest problems we actually have in management is trying to understand some of this differentiation between reliability and system safety. I have seen statements of work that say "failure mode analysis will be conducted." Now safety goes beyond that.

It is not only failures, you have the environment effect, you have personnel errors, you have a lot of other things that actually the reliability people did not consider and so in writing the statement of work, where it is the statement of work again it is necessary that they be clear in making sure this is a safety effort and not a part of a reliability effort. I might say that June 10th, Machine Design is going to have another article and it is going to be on reliability versus safety as related to liability. In this we point out the fact that indicating in warranties that an express warranty, where you say a thing will last a certain length of time, 50,000 miles or 5 years, is actually a warranty that relates to reliability. The implied warranty that a product must be safe if it has no time limit actually on the thing is really the system safety aspect of a liability suit. In addition to that I try to point out, the article was cut down, was the fact that if you have an accident and a liability suit arises, it doesn't matter what the test reliability or the operational reliability or the design reliability was, you can be sued for negligence in design and a lot of other things unless you have taken suitable safety action. There is a great difference between the reliability and the system safety but frequently, as I stated before, the expressions in the statement of work do not reflect. We then have trouble with management in trying to indicate that there is a difference.