

TITLE

Single Auxiliary Power Unit (APU) Landing – Manual Speedbrake Setting

PURPOSE

To describe the procedure for manually setting the speedbrake when the Shuttle lands with only a single APU operating.

BACKGROUND

The Shuttle software is designed to allow a landing with only one of three APUs operating. It does this by reducing the aerosurface drive rates to values that can be supported by a single APU. The software responsible for this function is called priority rate limiting software (PRL) and is discussed in detail in SCP 9.10, PRL MANAGEMENT. When this software was developed it was understood that single APU landings involved risk because they required that the remaining APU perform at its operational limits. However, it was believed that with the software in place a successful landing could be accomplished.

Studies conducted at the Ames Vertical Motion Simulator in April of 1998 to support APU hardware upgrades revealed serious flaws in the existing PRL software. It was discovered that the software consistently allowed APU overdemands in excess of 20 gallons per minute (gpm) during certain flight phases. Severe hydraulic system pressure drops (and probably loss of vehicle control) were expected under these circumstances. Most of these overdemands occurred after Shuttle weight-on-wheels (WOW) but some (less significant) problems were also identified during gear deploy.

Three primary culprits were identified as the causes of the overdemands:

1. Sluggish speedbrake (SB)
2. PRL did not account for all post-landing system flow demands
3. In-air landing gear deploy hydraulic flow was underestimated.

SLUGGISH SPEEDBRAKE (SB)

The sluggish SB problem is a result of two independent factors. First, with a single hydraulic system (and therefore a single hydraulic motor), SB responsiveness is significantly reduced. When the PRL software commands the SB to drive at a given rate, the SB does not achieve this rate immediately but takes 1-2 seconds to build up to it. This results in a command/position delta, with the actual SB position trailing the command position. This means that the SB will continue to move for 1-2 seconds after the software command stops in order to “catch up”. While SB lag is present even during 3 APU operation, it only becomes a factor during single APU operation. The other aerosurfaces also experience increased sluggishness during single APU operation but to a much smaller degree. Their lag is on the order of 0.3 seconds or less.

The second contributing factor to the SB sluggishness (although of less importance), is that the SB can not always achieve the drive rate commanded by PRL with a single hydraulic motor. Prior to OI-29, PRL software always commanded a SB open rate of 6.1 deg/sec and a close rate of 10.86 deg/sec, regardless of how many hydraulic systems were available. When only a single APU is operating, the SB may not be able to open at a rate of 6.1 deg/sec if the Shuttle is in a high qbar region where it must overcome large aerodynamic forces. The drive rate may be reduced, for example, to 5.7 deg/sec. Shuttle Engineering simulator data has also indicated that the SB cannot achieve a 10.86 deg/sec drive rate in the closed direction, even in a high Qbar region where aerodynamic forces assist the motion. The data indicates that a drive rate of only about 7.7 deg/sec can be achieved. The effect of this is to cause the SB to lag even further behind the command and further increase the command/position delta.

The SB lag can create significant hydraulic over-demands during periods of peak system operation. During these periods, the PRL software attempts to reduce hydraulic system flow by reducing aerosurface drive rates according to specific priorities. It first attempts to reduce hydraulic system demands by terminating SB motion. It does this by "freezing" the SB position command to whatever value is present when peak hydraulic demands are detected. In this way it reserves all of the available hydraulic flow for higher priority aerosurfaces including the elevons, rudder and body flap. If this is inadequate to bring hydraulic flow within limits, PRL next reduces elevon, rudder and body flap drive rates across-the-board to keep hydraulic demands within the capability of a single APU. Unfortunately, when PRL freezes the SB command, the SB continues to move for 1-2 seconds in order to "catch up" with the command. During this 1-2 second period, the SB uses hydraulic system flow (approximately 18 gpm) which the PRL software does not take into account. PRL is not a feedback system and assumes that the aerosurfaces follow commands exactly. In an attempt to reduce the hydraulic demand of the SB during a single APU entry, the rates were further reduced via additional software logic and I-loads to 6.06 deg/sec closing, and 5.43 deg/sec opening (CR's 92422 and 02384) and are discussed in more detail later.

HYDRAULIC OVERDEMANDS

Simulations run over a wide range of conditions demonstrated that there were three regions between the deorbit burn and wheel stop where the SB command/position delta problem could create hydraulic system overdemands. The first occurred at an altitude of 300ft when the main gear was being deployed. The second occurred between WOW and weight-on-nose-gear (WONG) and the third was immediately following WONG.

When the WOW flag is set, the SB is commanded by the AUTO system to open to 100% to provide aerodynamic braking. This is also a time when the elevons and rudder are very active controlling bounce, maintaining centerline, and executing Orbiter derotation. The elevons are often commanded to drive at their maximum rate of 13.9 deg/sec during this period. Four elevons driving at full rate consume nearly all of the hydraulic capacity of a single APU. Under these circumstances, PRL freezes the SB command and divides the available hydraulic flow between the elevons and rudder (the body flap is not active in this timeframe). Unfortunately, the SB does not stop moving when the command is frozen because it lags behind. This results in an 18 gpm overdemand for 1-2 seconds immediately following WOW. The same situation occurs at WONG, when the elevons are commanded to the full down position at maximum drive rates in order to provide load relief for the tires. If in AUTO, the SB is still in the process of opening to 100% at this time and will again cause system overdemands for 1-2 seconds. In addition, there are new flow demands placed on the hydraulic system following WONG which

are not accounted for by PRL software. These include post WONG leakage, brake flow and nose wheel steering flow. These flows add approximately 6 gpm of demand on the hydraulic system. The in-air overdemand which can occur during gear deploy is a much less likely source of overdemand than those which occurs near WOW and WONG. In this case, overdemand will only develop if the SB is moving during gear deploy and the vehicle is also encountering vehicle dynamics which require significant activity of the elevons and rudder. Such situations are uncommon.

Based on test data, an average APU can provide approximately 72 gpm of hydraulic flow at 3000 psi (PRL assumes 69gpm in high speed). As flow demands increase above this value, hydraulic system steady state pressure drops off drastically. When flow demands reach 80gpm, overall system performance becomes unpredictable. The pressure could drop low enough to engage the rudder hydraulic brake, freezing the rudder position. The elevons could become sluggish or begin to stall. They might also experience unequal hydraulic flow and become unbalanced. All of these events would leave the rudder and elevons in undesired positions and result in large command/position deltas. As the hydraulic system began to recover from the pressure drop, the large command/position deltas would further tax the hydraulic system by asking for large rudder/elevon position changes. All of these events would introduce vehicle control problems and further contribute to demands on the hydraulic system. Vehicle loss of control is a possibility.

WORKAROUNDS: OI-27

Several solutions were considered to eliminate the sluggish SB problem, including adding SB position feedback to PRL. Due to internal timing problems, this and other options proved unworkable (See Asc/Ent Flight Techniques Panel #154, Single APU Landing Study Status). The best solution identified was to eliminate SB motion during gear deploy, WOW to WONG, and throughout rollout by manually setting the SB to a fixed position prior to landing. This requires a manual SB procedure.

While the manual SB procedure was being developed, an unexpected problem was identified. This problem was caused by a difference between the SB in-air minimum limits and the post-WOW minimum limits. For OI-27 and earlier flights, the SB minimum allowable setting in the air was 15% and the minimum post-WOW setting was 25% (these values were specified by software K-loads). The 10% difference between the in-air and post-WOW K-load values created a problem because it meant that the SB would open to 25% at WOW whenever the in-air setting was less than this value. This motion occurred even if manual SB was selected. Opening from 15% to 25% left the hydraulic system vulnerable to system overdemands after WOW for a time period of approximately 2 seconds [time for SB to open from 15 to 25 percent = $[(25-15 \text{ deg})/(6.1 \text{ deg/sec})] = 1.6 \text{ sec}$. SB sluggishness would increase the length of this time to approximately 2 seconds].

One way to avoid SB motion at WOW would be to limit the manual in-air SB setting to 25% or greater. However, this would have the negative impact of reducing landing energy for cases when the true desired setting was 15%. Requiring a minimum setting of 25% would also add complication to the crew manual SB procedure. This was highly undesirable because this procedure is performed near touchdown and the crew's attention should be focused on landing. It was decided at the Ascent/Entry Flight Techniques Panel #154 (January 17, 1999) that it was best to set the SB to the desired setting at 3000 feet (even if it was less than 25%) in order to minimize landing energy impacts and procedural complexity. The risk introduced to the

hydraulic system by allowing the SB to open from 15% to 25% at WOW was considered the lesser of the two evils.

WORKAROUNDS : K-load Changes in OI-28

The reason for the difference between the in-air SB minimum setting and the post-WOW setting is interesting and has to do with the SB/rudder hardware design. The SB/Rud consists of two panels held in place by a conical seal as shown in Figure 1. When the two panels move in unison they provide a rudder function and when they move in opposition they provide a SB function. The panels are rotated by a mechanism within the seal. To allow maximum range of rotation of the panels, a notch was cut into the conical seal which allowed the rotary actuator arm of the trailing panel to slide into it. Unfortunately, the notch in the conical seal was not made large enough to accept the panel's rotary actuator arm. This situation was not discovered until after the vertical tail, along with the SB/Rud, had already been assembled.

Rather than disassembling the vertical tail and re-machining the conical seal notch (an expensive proposition), it was decided to accept the hardware as it was. This meant that software limits had to be imposed on the SB/Rud system to ensure that the rotary actuator arm was never driven into the conical seal notch. If this were to occur, the Rud/SB would probably still function but the thermal seal would be damaged. Without a healthy seal, significant thermal damage could result to the Rud/SB mechanism during early phases of the entry (thermal damage would probably not be of great concern late in the landing profile). At the very least it would be extremely expensive to repair the damaged seal.

The trailing panel will contact the conical seal when it is commanded to a value greater than 20 degrees. The panel position is a combination of the SB and Rud commands as shown in Figure 2. In order to protect the conical seal, software limits were imposed on both the SB and the rudder (CR 39590B, 7/18/81) to ensure that the resultant Rud/SB trailing panel command never exceeded 20 degrees (OPS 3 and OPS 6, PASS & BFS). There was also additional margin added to allow for 3 sigma RSS (root sum squared) hardware tolerances and a channel failed hard-over in the SB and the Rud. The values selected for the SB and Rud limits during the in-air phase of flight were slightly different from those selected for the post-WOW phase.

In the air, the SB minimum value was set to 15.0 degrees and the maximum rudder value was set to 24.1 degrees. This ensured that the trailing panel of the Rud/SB would never contact the conical seal. They allowed the greatest range of motion for the SB (15% to 100%) at the expense of some range of motion in the rudder (0 to 24.1 degrees). Since a rudder value greater than 24.1 degrees was never expected in the air, this was considered a good compromise. After WOW, however, the situation changes. The SB opens to 100% so a limit on the minimum setting is inconsequential. The rudder, on the other hand, becomes extremely important for maintaining directional control while the vehicle in the unstable two-point stance. Hence, the rudder capability was extended to 27.1 degrees and the SB capability was reduced by limiting its minimum value to 25%.

The values selected for the in-air and post-WOW SB/Rud limits made sense at the time they were selected but they created a problem for the single APU landing manual SB procedure. In order to remove the risk of the SB opening from 15% to 25% at WOW during a single APU landing, the AEFTP #154 decided to implement K-load changes in OI-28 (OPS 3 & 6, PASS and BFS). The in-air values will remain the same but the post-WOW values will be changed. The post-WOW SB minimum setting will become 15% and the maximum rudder setting will become 26.6deg. The rudder setting of 26.6 deg was derived by backing off of some of the

conservatism included in the in-air limit of 24.1 degrees. As mentioned above, the 24.1 degree limit protected for 3 sigma RSS hardware tolerances and a hardover channel failure in both the SB and rudder. The new value of 26.6 deg allows for 3 sigma RSS hardware tolerances but does not protect for any hardover channel failures.

Once the OI-28 K-load changes are implemented, the risk of SB motion at WOW will be completely eliminated and the majority of the single APU system overdemands will be corrected.

WORKAROUNDS : PRL UPGRADES in OI-29

To eliminate the remaining causes of hydraulic system overdemands, software upgrades were incorporated into PRL with OI-29. These changes include the following:

1. Increase gear deploy hydraulic flow from 6.64 gpm to 12.75 gpm
2. Add flows to account for post-WONG leakage (2.93 gpm), nose wheel steering flow (1.50 gpm) and brake flow (1.60 gpm).
3. Limit post-WONG elevator and aileron surface drive rates to 10.5 deg/sec (instead of 13.9 deg/sec).
4. Create new SB drive rate I-loads for single APU operation: 5.43 deg/sec (open); 6.06 deg/sec (close).

It is important to note that the 3K manual SB procedure is still required. Since attempts to incorporate aerosurface position feedback data into PRL failed (due to sampling rates and timing problems) it was not possible to fully eliminate hydraulic overdemands resulting from a sluggish SB with software changes alone. The new single APU SB drive rate I-loads of 5.43 deg/sec (open) and 6.06 deg/sec (close) reduce the magnitude of the SB command/position deltas which develop during SB motion but do not completely eliminate them. This means that overdemands due to SB motion can still occur during gear deploy and post-WOW unless the manual SB procedure is implemented.

The increase in gear deploy flow from 6.64 gpm to 12.75 gpm was made to bring the hydraulic flow value in line with current gear deploy estimates. Flight data shows that it takes approximately 5.6 seconds to deploy the landing gear. Since a fixed quantity of fluid is needed for gear deploy, the gpm during this time is calculated by taking this fixed quantity and dividing by the observed deploy time of 5.6 seconds. The original value of 6.64 gpm is believed to have been derived by using the spec value of 10 seconds for gear deploy. Since the actual deploy occurs much faster than the spec value, the gpm to deploy the gear was originally underestimated. The post WONG leakage of 2.93 gpm, brake flow of 1.60 gpm and nose wheel steering flow of 1.50 gpm were added to account for flow sources that were overlooked (or did not exist) when the PRL software was originally written. The reduction from 13.9 deg/sec to 10.5 deg/sec in elevator and aileron drive rates at WONG reduces elevon/aileron hydraulic flow demands and reserves greater flow for rudder activity. The rudder is extremely important for control authority during rollout since nose wheel steering may not be available when only a single APU is operating. The only negative aspect of reducing elevator and aileron limits is the possibility for a slight increase in tire and nose gear landing loads but these are acceptable.

The OI-29 software change which generated the most discussion involved the change in the SB drive rate. This change was implemented for two reasons. First, it minimizes the magnitude of the SB command/position deltas which can develop because it brings the commanded rate in closer agreement with the actual drive rate capability. Reducing the command/position delta reduces exposure to system overdemand while the Shuttle is in the air. Simulation data has not revealed any scenarios where a sluggish SB causes in-air overdemand (with the exception of the brief period during gear deploy) but this does not mean that such scenarios do not exist. The SB drive rate change provides increased protection from unexpected dynamics that could cause large hydraulic system demands during entry. Minimizing the SB command/position delta will also minimize the period of overdemand if such situations should develop.

The second, and primary reason, for reducing the SB drive rate for single APU operation is to protect the SB hardware. The certified drive rate for a single hydraulic motor is 5.43 deg/sec. The software prior to OI-29 commanded a single motor SB drive rate of 6.1 deg/sec in the open direction and 10.86 deg/sec in the closed direction. These values are clearly beyond the certified limit. While the "certified" value was not necessarily derived based on hardware capability, it represents a prudent limit for hardware operation. The OI-29 software changes were implemented to bring the single APU commanded drive rates closer to the certified values.

There were two competing issues which had to be considered when selecting the single APU SB drive rate. Reducing the drive rate to the certified limit would guarantee safe hardware operation but would have negative impacts on landing energy (because the SB would take longer to close at 3000 ft). A faster drive rate would improve landing energy impacts but might compromise hardware integrity. A value had to be selected which provided reasonable hardware protection while ensuring acceptable landing energy conditions.

The difference between the pre-OI-29 SB open drive rate of 6.1 deg/sec and the certified limit of 5.43 deg/sec was considered trivial so the certified limit was selected. No impacts on flight control or landing energy were identified for this change. Selection of the close drive rate proved to be a greater challenge. Data from the Shuttle Engineering simulator (SES) indicated that a single motor could probably only achieve a maximum SB closed rate of about 7.7 deg/sec. The fidelity of this simulator was unclear but represented the best available estimate of hardware capability. This placed an upper bound on the software close rate limit of 7.7 deg/sec.

The vendor, Hamilton Sunstrand, reported that the PDU hydraulic motor had a rated speed of 7000 rpm which corresponded to a 5.4 deg/sec drive rate. The suppliers performance data showed that the overspeed capability of the motor was 9900 rpm for up to ten minutes which corresponded to a drive rate of 7.7 deg/sec. However, there was no test data available to substantiate the performance data values. The only test data available which demonstrated that the SB motor could safely operate faster than 5.43 deg/sec was collected during hydraulic motor acceptance testing (AT). The data showed that a motor operated safely at a rate of 6.06 deg/sec for approximately 10 seconds.

The landing energy impacts of operating the SB at a close drive rate of 7.7 deg/sec vs. 6.06 deg/sec were examined using the landing conditions from ten selected shuttle flights. No significant impacts were identified on the Shuttle's ability to track the reference velocity on the outer glide slope. A reduction of about 200 feet of landing energy was observed in the worst case flight (STS-56). Based on this information, the AEFTP Splinter Meeting (February 8, 2000) decided to implement a drive rate of 6.06 deg/sec in the SB close direction. The Flight

Techniques Panel felt that the 200 feet of additional landing energy which could be realized by driving the SB at 7.7 deg/sec did not warrant the risk of operating the system outside of demonstrated limits. The new limits will be implemented in OI-29 and in the landing energy simulation used by the flight dynamics officer (FDO) to predict landing energy for single APU operations.

The manual SB procedure in conjunction with the OI-29 software changes should eliminate any serious hydraulic system overdemands. The worst-case flow overdemands are expected to occur between WOW and WONG and to be less than or equal to 75 gpm. Flow demands over 69gpm are expected to be limited to 1.5 seconds or less. The hydraulic system pressure drop associated with these worst-case overdemands is predicted to be on the order of 800psi. Any pressure drop in excess of 600 psi will generate a master alarm, illuminate the F7 panel light and generate a BFS "Hyd PRESS" fault message. Analysis of representative Ames vertical motion system overdemand cases show that transient pressure spikes due to waterhammer effects will approach or potentially slightly exceed the hydraulic system limits of 4500 psi (component proof pressure requirement) but should stay well below 6000 psi (tubing proof pressure requirement). Refer to the Orbiter Review Board (ORB) presentation of August 1, 1999, for more details.

All post-WONG over-demands are expected to be very short spikes (<160ms) due to nose wheel steering inputs. These short duration spikes are not expected to have a notable impact on system pressure. The in-air overdemands were predicted to be less than 0.2 seconds in duration and should also have a negligible effect on system pressure.

Unapproved OI-29 Software Changes

It should be noted that additional software changes were evaluated but not implemented when the OI-29 software changes were developed. These additional changes were intended to reduce flow demands between WOW and WONG and included the addition of a 2.93 gpm leakage term and a reduction in aileron & elevon rates from 13.9 deg/sec to 10.5 deg/sec at WOWLON. These changes were dropped because they were found to aggravate an undesirable bounce/oscillation condition at WOW. This phenomenon was first identified during testing in the vertical motion simulator at Ames Research Center. It was found to occur for all of the PRL configurations (including the original baseline configuration) but was encountered more frequently during landings with the changes implemented between WOW and WONG. It occurred in 15% of the landings with the WOW to WONG changes but only 4% of the baseline PRL landings. The increased bounce was primarily due to the reduced elevator rate capability and corresponding reduction in the control system's ability to damp the bounce oscillations. The magnitude of the oscillatory behavior was a function of several variables including mass properties, wind conditions, aerodynamics, sink rate, equivalent airspeed and touchdown pitch attitude. The AEFTP #158 determined that the lesser of two evils was to accept some hydraulic flow overdemand between WOW and WONG in order to avoid exciting the undesirable "bounce" effect.

MANUAL SB PROCEDURE

During nominal entries the SB is kept in AUTO for the entire entry profile. At an altitude of 3000 feet, the AUTO system commands the SB to a fixed position for landing. This position is a function of the Shuttle predicted landing energy. The SB stays at its 3K setting until an altitude of 500 feet, where a final adjustment is made by the AUTO system to ensure proper energy for landing. When the crew performs a single APU landing, the SB also remains in AUTO for most

of the entry profile. The only difference is that the 3K SB positioning is executed by the crew instead of by the AUTO system; and there is no 500ft adjustment.

When the manual SB procedure was being developed, two different options were considered for determining what value the crew should use when setting the SB. The first option considered was for the crew to match the on-board AUTO SB command at 3K. This option was found to be cumbersome because it was a challenge for crews to accurately match the AUTO setting in the short time available between 3K and gear deploy at 500 ft.. Of even greater significance was the fact that this technique was time consuming and distracted the pilot's attention from higher priority tasks associated with landing. A second option was developed in which the crew was given a 3K manual SB setting by the Flight Dynamics Officer (FDO) on the Entry DEL PAD, along with a reminder to use the manual SB procedure (if a single APU landing situation was expected). The SB setting was updated, if necessary, via the Capcom, during the final winds and weather update call as the Shuttle approached the heading alignment cone (HAC). In order to keep the procedure as simple as possible and thereby minimize crew distractions, the pilot set the speedbrake/thrust controller (SBTC) to the proper position using the cue card located next to the SBTC handle. Refer to the "Speed Brake Cmd vs. SBTC Trailing Edge" cue card in the Ascent Checklist. This action was performed during a quiescent period early in the entry profile in preparation for the manual 3K setting. The SB remained in AUTO during this time. At 3K, the pilot engaged the SBTC manual takeover push-button on the SBTC handle to invoke manual SB control. Since the SBTC was already properly positioned, the SB would be commanded to the correct setting. No further action was required by the crew other than to confirm that the SB was at the desired position using the surface position indicator (SPI) or CRT.

The FDO will round the preferred SB position to the nearest 5 degrees to make it easier for the crew to set the SB. The crew should make a best effort to achieve the proper position since any errors will have impacts on landing energy. However, they should not allow themselves to become distracted by attempting to fine tune the SB position. Not only would such activity divert the crew's attention from the higher priority activities of landing but it would also introduce the possibility of SB motion during gear deploy or close to the ground when the elevons are making last minute adjustments. In both cases, SB motion could result in hydraulic system overdemand. The most important objective for the crew should be to get the SB set reasonably close to the desired value and then leave it alone. Once the SB has been positioned to the 3K setting, the crew should not move it again until after wheel stop.

There may be landing scenarios where runway length is limited and opening the SB after touchdown to reduce rollout distance becomes highly desirable. This would only be a concern at selected contingency or transatlantic (TAL) abort sites with short runways. Since a single APU landing in combination with a contingency/TAL abort is extremely unlikely, the manual SB procedure was not developed to accommodate this scenario. However, if such a situation occurs, the crew may safely open the SB during rollout if they wait at least four seconds after WONG. A four second delay will ensure that the elevons have completed the movement from a full up position of -11.7 deg (typical during derotation) to a full down position of $+22.5$ deg (for load relief) and that system overdemand is no longer a threat. The crew should be especially careful not to move the SB between WOW and WONG since this is the period of greatest hydraulic system stress and of flight control instability.

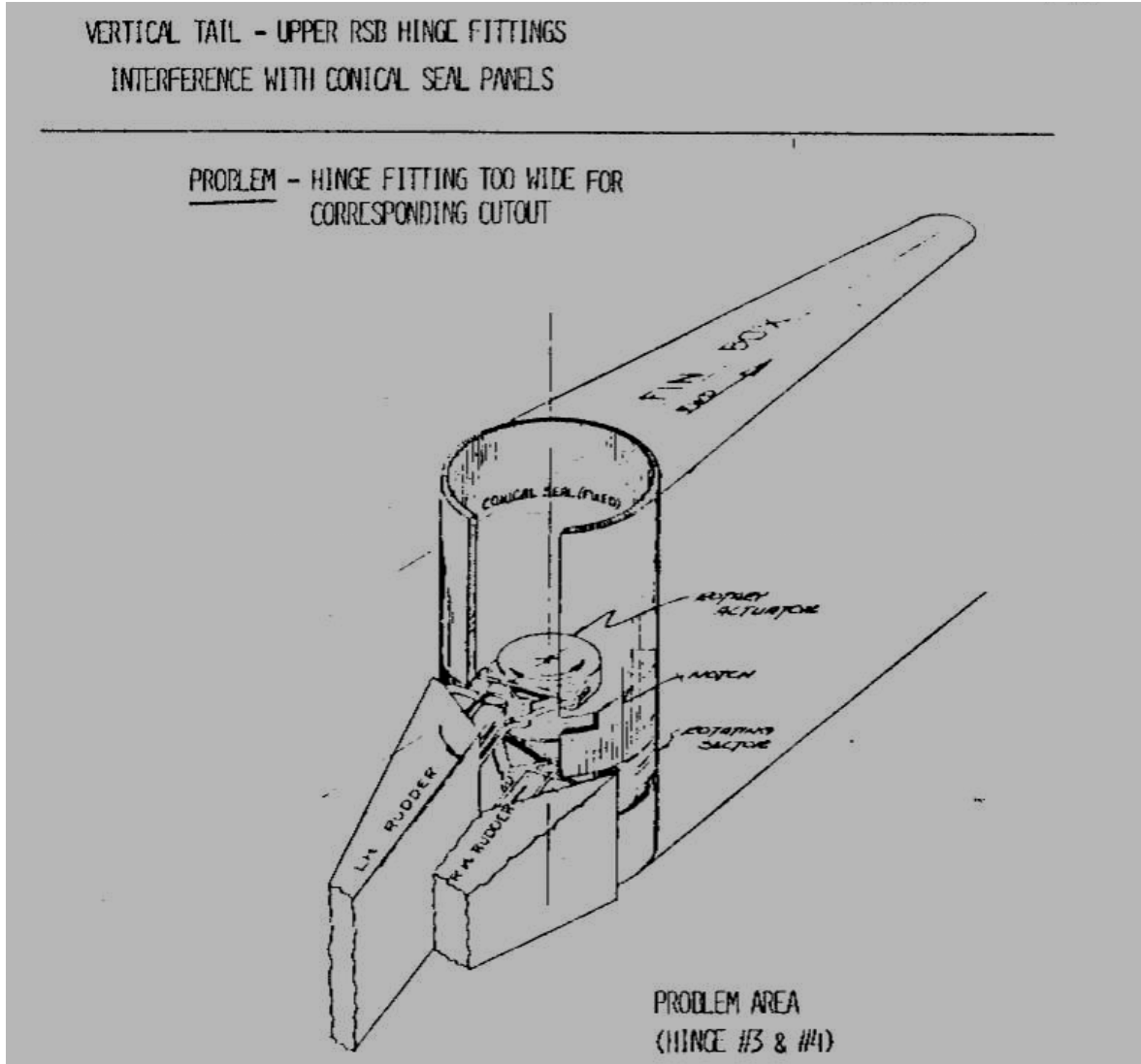


Figure 1: SB/RUD Conical Seal

$$\text{Rud Trailing Panel (TP) Pos} = \text{Rud cmd} - 1/2(\text{SB cmd}) < 20 \text{ deg}$$

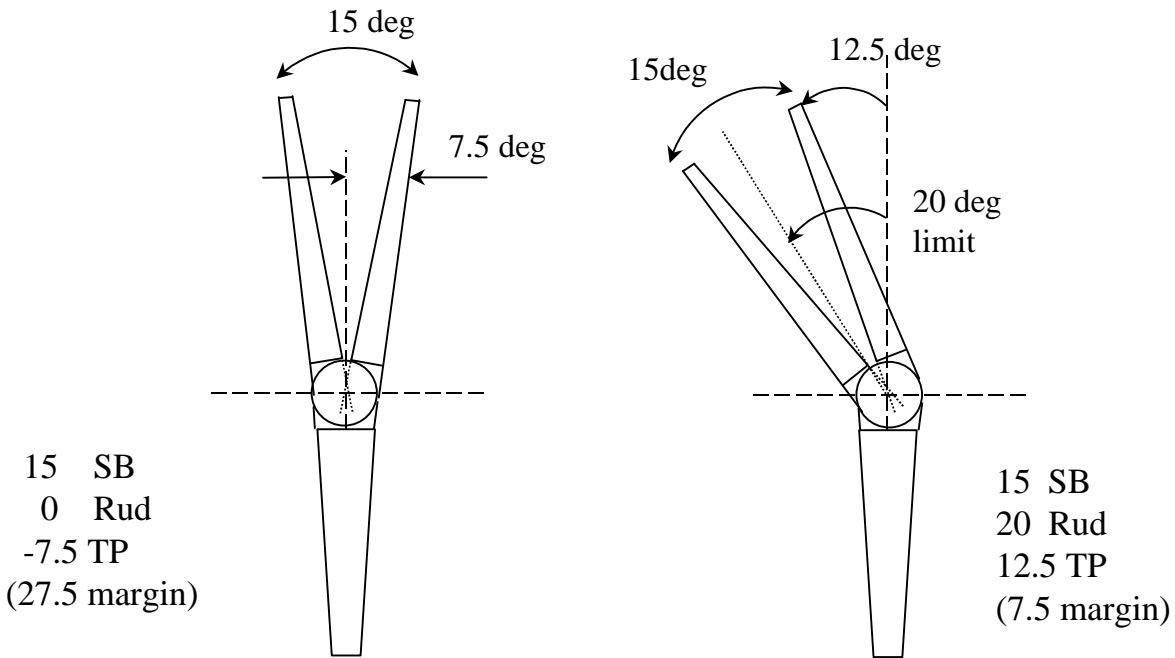


Figure 2: Trailing Panel Deflection

References:

1. ORB Presentation, August 3, 1999, "Feb-March '99 Ames Vertical Motion Simulator (VMS) Results (Kyle Cason)
2. Ascent/Entry Flight Techniques Panel #158, June 25, 1999, "Feb-March '99 Ames VMS Results (Kyle Cason, Bill McDermott, Ed Digon)
3. Ascent/Entry Flight Techniques Panel #154, January 27, 1999, "Single APU Landing" (Laura Kavanaugh)
4. Ascent/Entry Flight Techniques Panel Splinter, February 8, 2000, "Single APU Speedbrake Rate Limits" (Kyle Cason, Bill McDermott, Boeing); "A&L T/D Energy Concerns (Alan Hochstein)