4111 Bridgeway Avenue, Columbus OH 43219

NETJETS®

December 14, 2011

Mr. Robert Gretz
Senior Air Safety Investigator
National Transportation Safety Board
490 L'Enfant Plaza, SW
Washington, DC 20594

Via Email

Re: Investigation ERA11IA316

Dear Bob,

Please find enclosed the NetJets Aviation, Inc. party submission for National Transportation Safety Board (NTSB) Investigation ERA11IA316, involving N749QS in Newburg, NY (KSWF) on May 27, 2011.

NetJets Aviation, Inc. appreciates the opportunity to participate in the investigation and respectfully request consideration of the attached information in the NTSB's finding of probable cause.

If you have any questions, please do not hesitate to contact me at 614-239-2695.

Sincerely,

[redacted]

Paul McClaskey
Director, Aviation Safety
NetJets Aviation, Inc.

Party Submission

Regarding

Landing Gear Collapse during Landing

Israeli Aircraft Industries Gulfstream 200

Newburg, NY

May 27, 2011

NTSB Investigation ERA11IA316

NetJets Aviation, Inc.
4111 Bridgeway Ave.
Columbus, OH 43219

December 15, 2011

Executive Summary

An Israeli Aircraft Industries Gulfstream 200 experienced a collapse of the right main landing gear after touch down resulting in minor damage to the aircraft. The crew had experienced landing gear extension difficulties prior to the landing. The difficulties included failure of all three landing gear to indicate down and locked upon initial extension and failure of the emergency landing gear extension system to resolve the problem.

The cause of the incident appears to be improper rigging of the landing gear control cable resulting in the normal landing gear extension system being unreasonably sensitive to the positioning of the landing gear handle in the down position. Further, the design of the emergency landing gear extension system coupled with the emergency landing gear extension abnormal procedure checklist design did not provide resolution of the issue.

Recommendations are made to review the landing gear control cable rigging procedure, provide positive detents for the landing gear control handle in the up and down positions and modify the landing gear normal and emergency extension systems to provide reliable extension of the landing gear under all identifiable failure modes.

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Introduction

On May 27, 2011, about 09:28 eastern daylight time (EDT), an Israeli Aircraft Industries Gulfstream 200, N749QS, received minor damage when its right main landing gear collapsed while landing at Stewart International Airport (KSWF), Newburg, NY. The flight had originated from Greenville-Spartanburg International Airport (KGSP), Greer, SC with an intended destination of Westchester County Airport (KHPN), White Plains, NY.

Approaching KHPN at 170 KIAS and 2,000 feet, the Captain called for gear down and the before landing checklist. The crew reported hearing noise associated with gear extension, but all three Engine Indication/Crew Alerting System (EICAS) landing gear position indications were red, indicating the landing gear was not down and locked. The crew abandoned the approach and requested holding while they ran checklists. The landing gear handle was left in the down position. Once at a safe altitude, the crew initiated the Landing Gear Down Lock Indication Failure checklist.

Approximately two and one half minutes after the landing gear was first extended, the crew received a HYD OVERHEAT R Crew Alerting System (CAS) caution message. They noted that the right hydraulic temperature was 85 C and the hydraulic pressure was 1400-1500 psi (normal is 3,000 psi). The crew initiated the Hydraulic System Overheat abnormal checklist. This checklist directed the crew to reduce thrust on the right engine to idle, which the crew accomplished. The crew noted that the right hydraulic system temperature cycled up and down and the hydraulic system pressure remained low for the rest of the flight.

Next the crew ran the Emergency Landing Gear Extension abnormal checklist. After completing the checklist, the crew noted that the nose gear position indicated down and locked, however both main gear indications were still red. After flying past KHPN tower, the tower advised that all three landing gear appeared down. At this point, the crew declared an emergency and requested to divert to KSWF due to the unsafe gear indications and right hydraulic system issues. The crew departed the KHPN area at approximately 09:15 EDT.

En route to KSWF, the Captain requested the Right Main Hydraulic System Failure abnormal checklist to be read and reviewed. The First Officer briefed the passenger on the diversion to KSWF, the possibility of landing gear collapse and the actions necessary in that event.

Approximately 15 minutes after departing KHPN, the flight arrived at KSWF. The crew made a visual approach to runway 27. Touchdown and initial roll out were normal, however, the right main landing gear did not support the weight of the aircraft and the aircraft settled on the right wing tip. The Captain was able to keep the aircraft on the runway center line and brought the aircraft to a stop. Subsequently, the First Officer and the passenger evacuated the aircraft through the main cabin door. The Captain secured the aircraft and evacuated through the main cabin door.

Investigation

The National Transportation Safety Board (NTSB) initiated an investigation into the accident under case number ERA11IA316. NetJets Aviation, Inc. (NJA) is a party to that investigation along with the NetJets Association of Shared Aircraft Pilots (NJASAP), Gulfstream Aerospace Corp. (GAC) and the Federal Aviation Administration (FAA).

Factual Information Emphasis

The factual information developed during the investigation is a joint product of the parties and is well documented in the docket. However, a few portions of the factual information warrant special emphasis.

Landing Gear Extension and Retraction System

The aircraft is equipped with a normal landing gear extension and retraction system and an emergency landing gear extension system. The normal system utilizes Right Hydraulic System (RHS) pressure to retract and extend the landing gear. In case of RHS failure, emergency landing gear extension is accomplished by using nitrogen compressed at 3,000 psi in an emergency extension bottle. The emergency extension system uses separate pneumatic lines connected to the landing gear actuators through shuttle valves installed on the actuators. The return line for the emergency landing gear extension system is common with the normal extension and retraction system.

Extension and retraction of the landing gear is controlled by a two-position landing gear selector valve, mechanically linked with a push-pull control cable to the landing gear control handle on the instrument panel. When the landing gear is down and locked, three green landing gear position indication boxes (with DN inside the box) are displayed on the primary page of the EICAS.

When the landing gear control handle is selected to the up position, RHS pressure is applied through the dump valve to unlock and to retract main landing gear, unlock the nose landing gear unlock actuator and extend the nose landing gear actuator. The landing gear is locked in the up position by mechanical locks. With the landing gear control handle in the UP position, the hydraulic mechanisms remain pressurized.

During the retraction cycle, the three landing gear position indication boxes on the EICAS change color to amber with a barber pole displayed inside the box. When the landing gear is up and locked the three landing gear position indication boxes on the EICAS change to white with UP displayed inside the box.

When the landing gear control handle is selected to the down position, hydraulic pressure is applied to unlock the landing gear uplocks and to the actuators to extend the landing gear. During the extension cycle the three landing gear position indication boxes on the EICAS change to amber with a barber pole displayed inside the box. Once extension is complete, the three landing gear position indication boxes on the EICAS change color to green with DN displayed inside the box. If the extension time exceeds a pre-programmed limit, the EICAS landing gear indicators turn red. With the landing gear control handle in the down position, the hydraulic mechanisms remain pressurized.

Emergency extension of the landing gear is accomplished by placing the landing gear control handle to the down position and then releasing and pulling the emergency gear handle located on the left side of the center pedestal. The emergency gear handle actuates a push-pull control cable which in turn actuates the emergency selector valve. The emergency gear selector valve releases nitrogen pressure to the emergency port of the uplocks and to the landing gear actuators through shuttle valves. This drives all the landing gear to the down and locked position. Nitrogen pressure also triggers the dump valve. When the dump valve is actuated, it connects the retraction lines directly to return. This is designed to prevent hydraulic pressure in the retract system from inhibiting emergency landing gear extension.

A detailed schematic of the portion of the hydraulic system that accomplishes landing gear extension and retraction is shown in Figure 1 – Hydraulic system schematic.

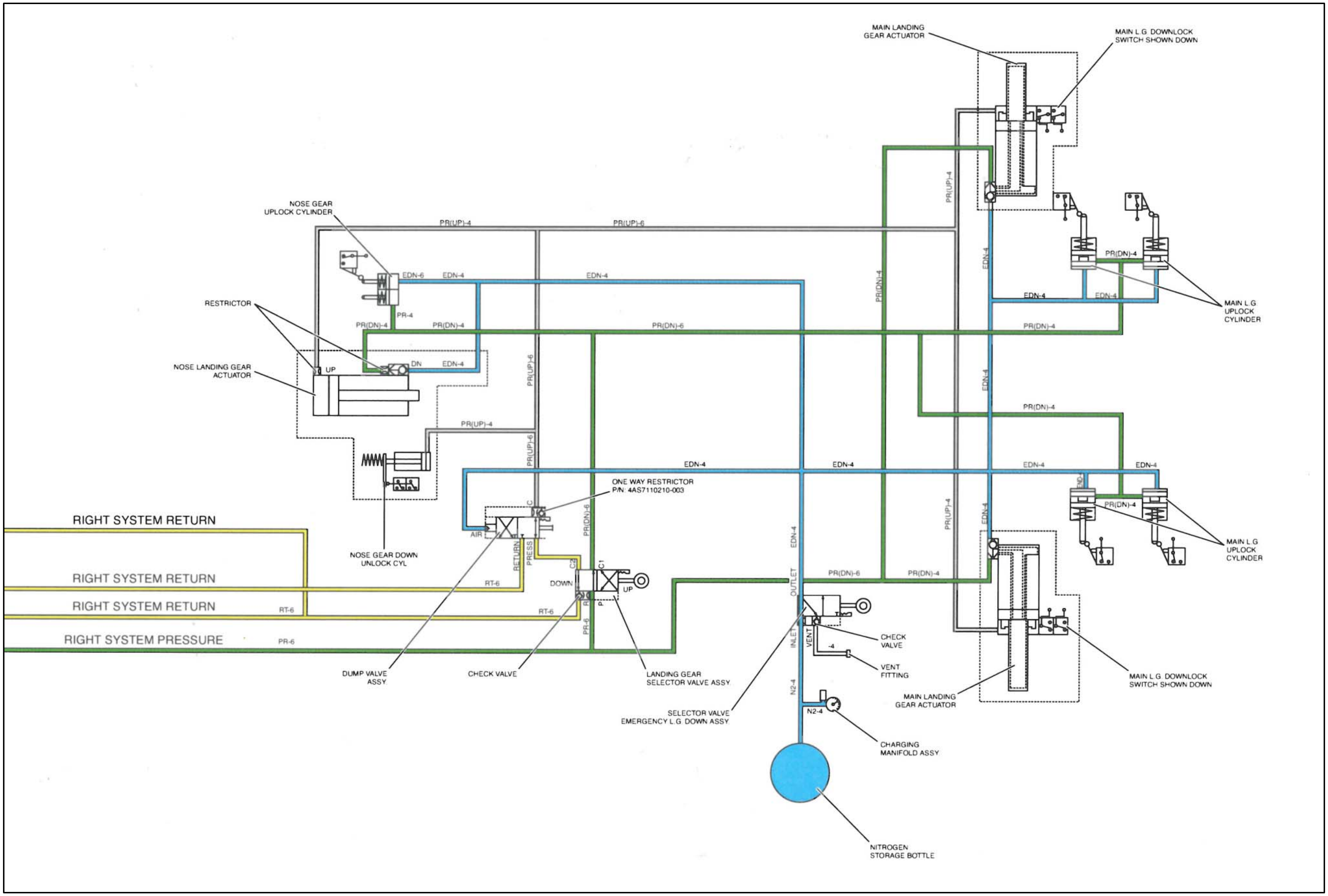

Figure 1 – Hydraulic system schematic

Hydraulic Power Supply

RHS hydraulic pressure is normally supplied by an engine driven pump (EDP). The EDP is a variable displacement, constant pressure pump. The pump is designed to provide a nominal pressure of 3,000 psi. A pressure switch monitors pump output pressure and activates the R HYD PUMP PRESS LOW CAS caution message when the pressure falls below 1,300 psi.

As a back-up to the EDP, the system has an electric motor pump (EMP). This pump is also a variable displacement constant pressure pump. The EMP provides 3,000 psi pressure at zero flow. As the flow rate increases, pump output pressure drops to 1,500 psi at a flow rate of 2.9 gallons per minute (GPM). A pressure switch monitors pump output pressure and activates the AUX HYD PRESS LOW CAS caution message when the pressure falls below 900 psi. The pump automatically activates whenever the RHS pressure falls below 1,300 psi. Activation is indicated by the AUX HYD PUMP ON CAS caution message.

RHS pressure is displayed on the EICAS for pilot reference. System pressure is the greater of the EDP and EMP pressures.

A detailed schematic of the portion of the hydraulic system that accomplishes landing gear extension and retraction is shown in Figure 2 – Hydraulic power supply.

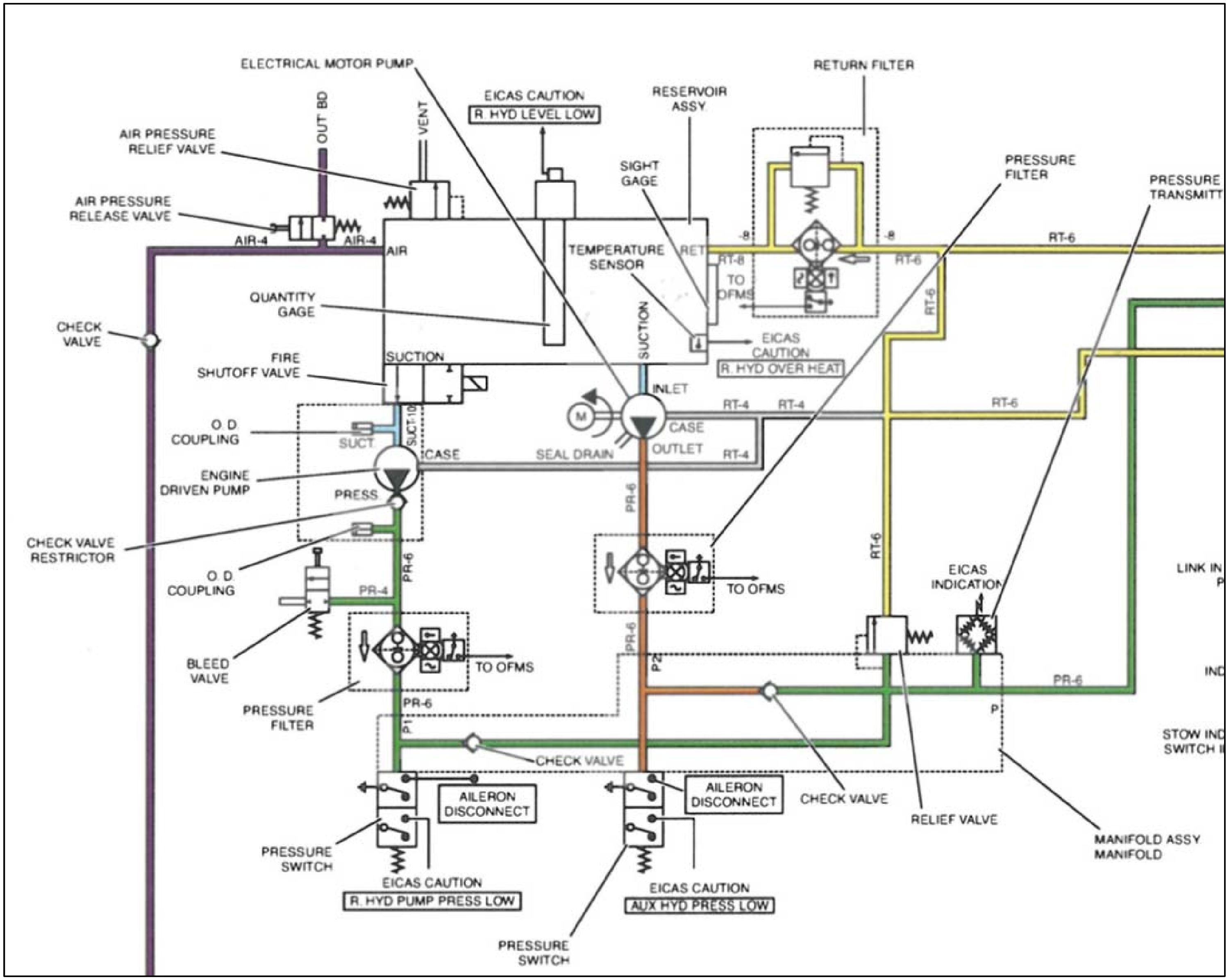

Figure 2 – Hydraulic power supply

Landing Gear Selector Valve Design

During the investigation, GAC provided the parties with a drawing for the landing gear selector valve, drawing number 9 3451.0000.000 Rev. f. A portion of the drawing is reproduced in Figure 3 – Excerpt from landing gear selector valve drawing.

As annotated in Figure 3, the down position can be assigned the 0 degree position and the up position is therefore the 90 degree position. The physical travel is limited by mechanical stops at the -5 degree position and at the +95 degree position.

The first item of emphasis is that detents are provided at the 0 and +90 degree position. These detents are a ball and spring design as indicated in the teardown report for the landing gear selector valve.

The second item of emphasis is the specification for interflow described in the drawing. Between the -5 and +10 position and also between the +80 and +95 degree positions, interflow is not permitted. In other words, when the valve is between the -5 and +10 degree position, flow is only permitted from the pressure port to the extend port and from the retract port to the return port. Other flow paths are not permitted. Likewise, when the valve is between the +80 and +95 degree positions, flow is only permitted from the pressure port to the retract port and from the extend port to the return port.

Within the range of +10 to +80 degrees, interflow is permitted, although its characteristics are unspecified. Typical flow modes would involve a proportion of the pressure present at the pressure port being applied to the other three ports (extend, retract and return). Resulting flow would be determined by the exact position of the valve and other system characteristics. Of particular interest is the flow from the pressure port to the return port under the interflow condition. This flow is termed “bypass flow”.

Interflow or bypass flow is an undesirable characteristic of a hydraulic system. When interflow conditions exist, the system will not perform as designed.

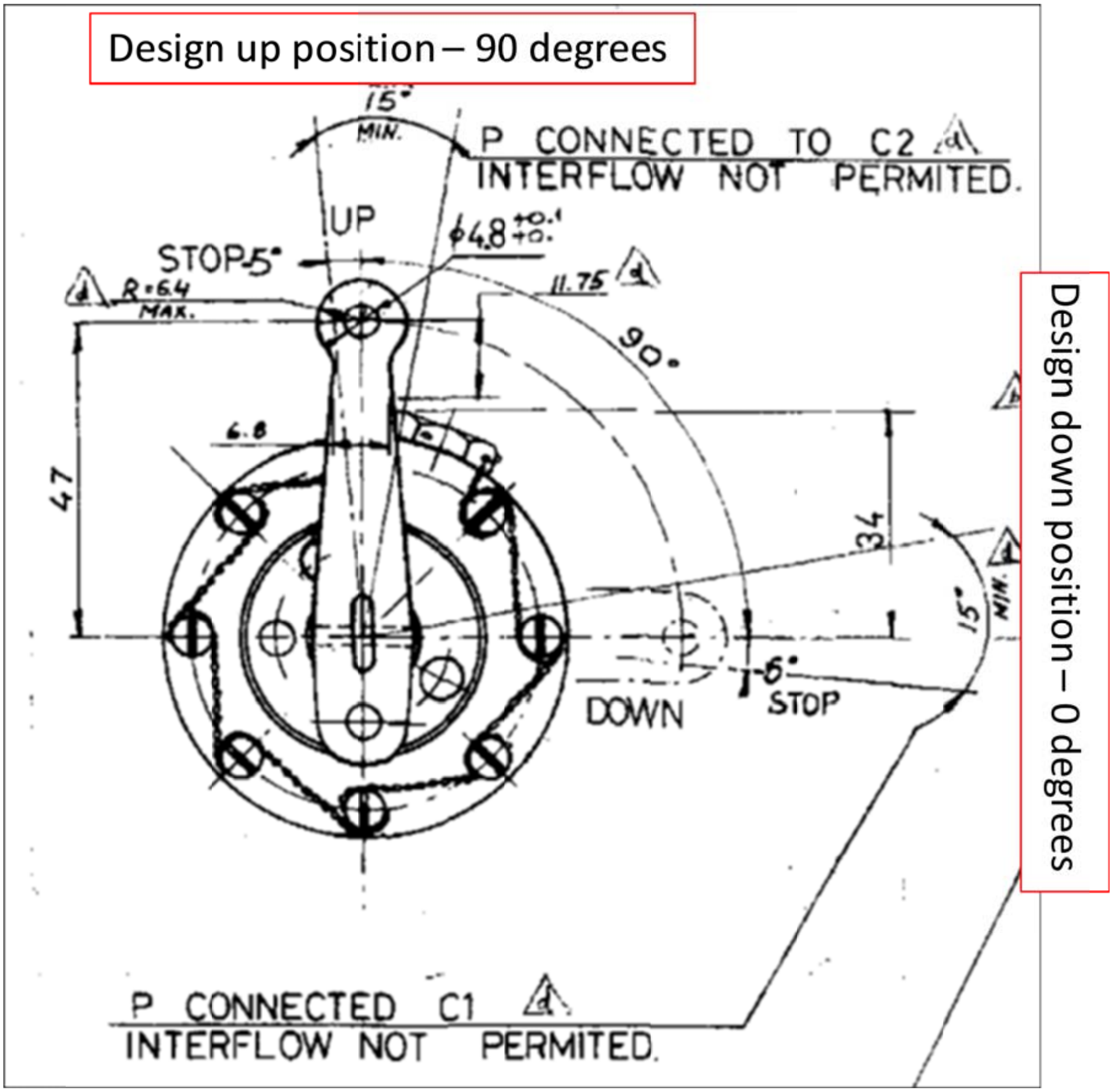

Figure 3 – Excerpt from landing gear selector valve drawing

Landing Gear Selector Valve Testing

Subsequent to the incident, the landing gear selector valve was removed from the aircraft and sent to the manufacturer for testing. Test results were provided in Israeli Aircraft Industries document 4AS716/111157. The manufacturer indicated that no defects were noted during the initial visual inspection, acceptance test procedure and teardown.

Section 4.3 of the landing gear selector valve teardown report describes additional testing done beyond what is required by the acceptance test. One test measured the onset of bypass flow as the valve was moved from the down position (0 degrees) toward the up position (90 degrees). The test noted that bypass flow initiated at 20 degrees, reached 3 gpm at 20.5 degrees, 6 gpm at 21.5 degrees and 10 gpm at 22.5 degrees.

A second test measured the torque to move the landing gear selector valve lever to be 14 in-lbs in between the ball/spring detents and 19 in-lbs coming out of the ball/spring detents.

Landing Gear Control Handle

The landing gear control handle itself does not appear to provide any tactile feedback or positive positioning detents in either the up or down positions. Any tactile feedback to the operator comes from the detents in the landing gear selector valve as transmitted through the landing gear control cable to the landing gear control handle.

Work Order Items

On May 22, 2011, the aircraft entered the GAC maintenance facility in Savannah, GA for correction of a fault in the windshield heat system and completion of NetJets' maintenance checklist for the G-200 aircraft. The work order number was SC238654. Excerpts from the work order are included in the docket.

The corrective action for the windshield heat problem was to replace the co-pilot's windshield.

As a result of completing the maintenance checklist, several minor maintenance actions were completed. These included replacing the right inboard main landing gear tire and wheel due to tire wear, investigation of a possible nose gear up lock actuator leak, cleaning and treating minor corrosion on the landing gear dump valve mounting hardware and replacement of the landing gear selector valve rod end due to corrosion.

Squawk 8.17 and its sub items describe replacement of the landing gear control cable rod end adjacent to the landing gear selector valve. See Figure 4 – Landing gear control rod end replacement for location of the rod end. The action includes reference to maintenance manual task 32-30-10 which is titled Landing Gear Control Cable – Removal/Installation.

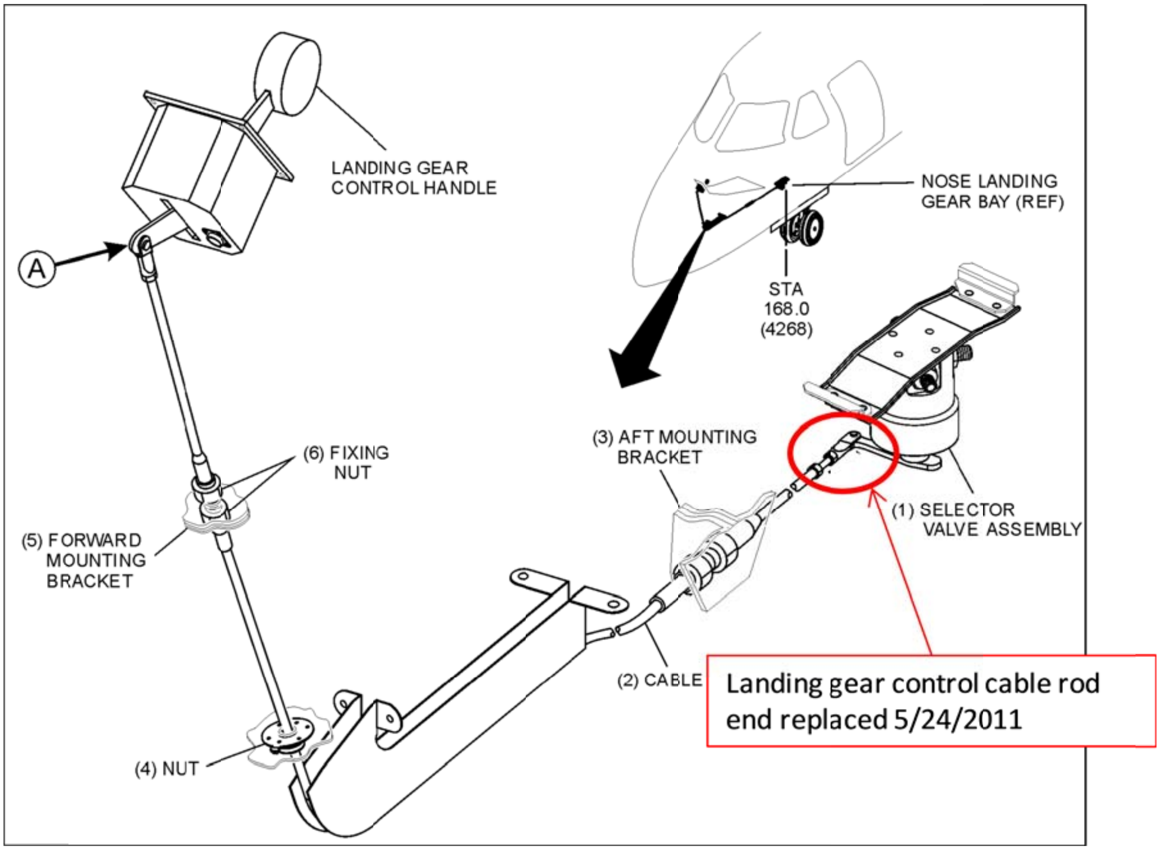

Figure 4 – Landing gear control rod end replacement

Subsequent to this maintenance, the work order indicates that the landing gear was cycled 20 times according to the procedures described in maintenance manual 32-30-00 B steps 14 and 15. These steps exercise the normal extension and retraction system. They do not exercise the emergency extension system or check the pressures necessary for unlocking, moving and locking the landing gear.

The aircraft was released from maintenance on 5/26/2011.

Rigging procedure

Although the landing gear control cable was not being replaced in its entirety, maintenance manual task 32-30-10, Landing Gear Control Cable – Removal/Installation, was probably the most relevant technical guidance for replacing the rod end. A copy of this task has been included in the docket.

Part C, Installation, step (5) directs the technician to place the landing gear control handle in the down position. As noted above, the landing gear control handle does not have detents associated with the up or the down position. As a result, placing the landing gear control handle in the down position is subjective. One technician's opinion of the down position might differ from the opinion of another technician.

Part C, Installation, step (6) directs the technician to place a quick release rigging pin in the landing gear selector valve to lock it in the down position.

Part C, Installation, step (10) directs the technician to adjust the control cable rod end so that there is a minimum of 0.078 inches of clearance between the thread end and the rubber seal. This step is necessary to ensure the threads on the rod do not damage the rubber seal during operation. This adjustment may result in changes in the position of the landing gear control handle.

Subsequent to completing this adjustment, there is not a step to verify that the landing gear selector valve can be moved from stop to stop without the landing gear handle reaching the limits of its travel. Likewise, there is no step to verify that moving the landing gear control handle to the limits of its travel will result in the landing gear selector valve reaching its proper position within either of the no interflow angular zones.

Main gear actuator testing

Subsequent to the incident, the right main landing gear actuator was removed from the aircraft and sent to the manufacturer for testing. Test results were provided in Israeli Aircraft Industries document DOC 26318, an excerpt of which has been included in the docket. The manufacturer indicated that no defects were noted during the initial visual inspection, acceptance test procedure and teardown.

Redacted from the document are the acceptance test results which were shared with the parties during the investigation. Of particular interest is test number 16 regarding CMM reference items 6 (g) and (h) in the test results.

For CMM reference item 6(g), the extend port (Port A) has an applied pressure of 580 psi and the retract port (Port B) has an applied pressure of 150 psi. The cylinder is in an extended but unlocked condition. The pressure on the extend port is slowly increased until the actuator locks. The locking pressure in this situation is specified to be less than 940 psi at the extend port. During the test of the actual actuator, the cylinder locked as the extend pressure was increased to 800 psi.

For CMM reference item 6(h), the extend port (Port A) has an applied pressure of 2,680 psi and the retract port (Port B) has an applied pressure of 800 psi. The cylinder is in an extended but unlocked condition. The pressure on the retract port is slowly decreased until the actuator locks. The locking pressure in this situation is specified to be greater than 240 psi at the retract port. During the test of the actual actuator, the cylinder locked as the extend pressure was decreased to 280 psi.

The significance of this test is that when extending the landing gear with approximately normal hydraulic system pressure on the extend port, the actuator will not lock down and indicate a locked condition until the pressure on the retract port is reduced to 280 psi. In addition, this requirement is specified as a pressure greater than 240 psi. Therefore, the design pressure at the retract port during landing gear extension must be less than 240 psi in all cases in order to ensure down lock under allowable manufacturing tolerances. This condition must be met regardless of the pressure applied to the extend port.

Landing gear control handle/landing gear selector valve position

During the field portion of the investigation just after the incident, the position of cockpit controls and switches was photo documented. This documentation was accomplished prior to any movement of controls or switches and before power was applied to the aircraft.

The position of the landing gear control handle was photographed and is included in the docket. That photograph is reproduced in Figure 5- Landing gear control handle position. As the photo shows there is still room to move the handle further down as evidenced by the space between the bottom of the handle and the bottom of the handle slot.

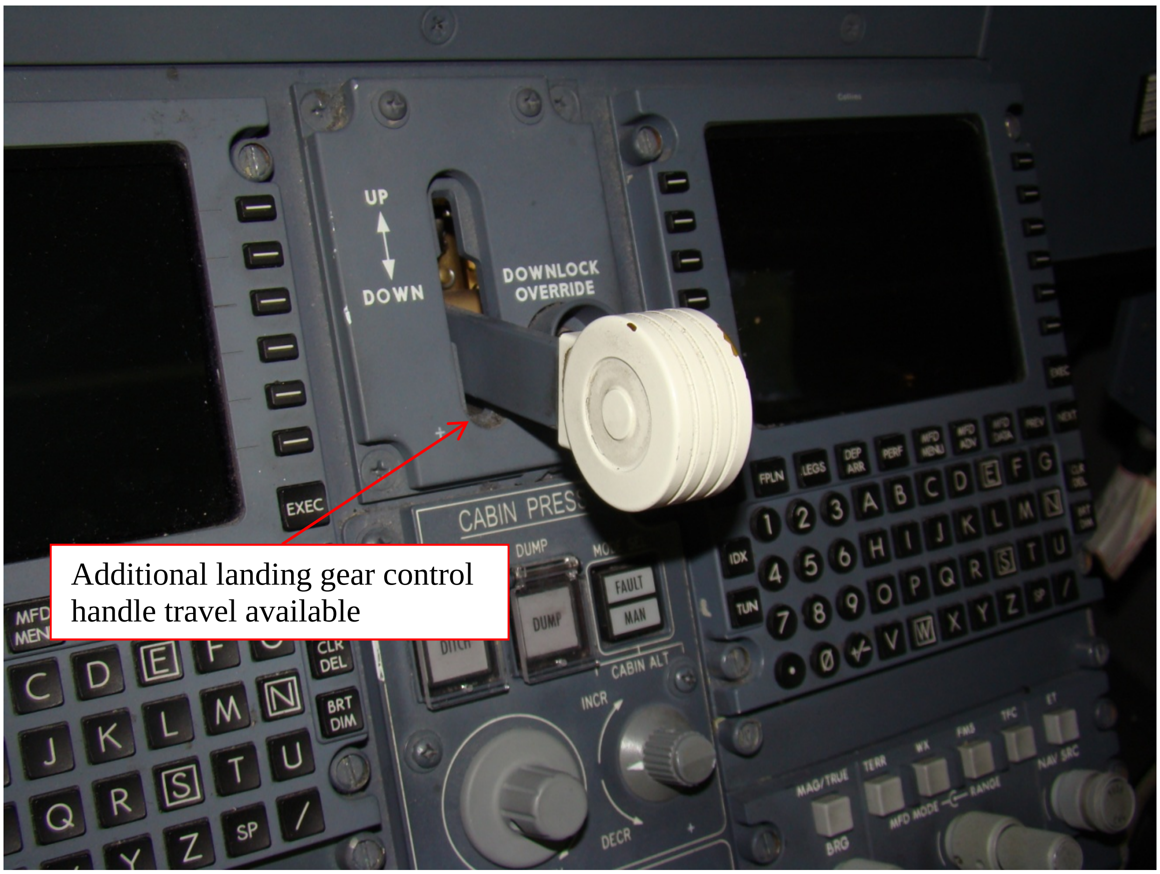

Figure 5 – Landing gear control handle position

The position of the landing gear selector valve was also photographed and is included in the docket. That photograph is reproduced in Figure 6 - Landing gear selector valve position – Photo 1. Even though the camera was not square with the position of the valve it is clear that the rigging pin holes in the valve are not in alignment.

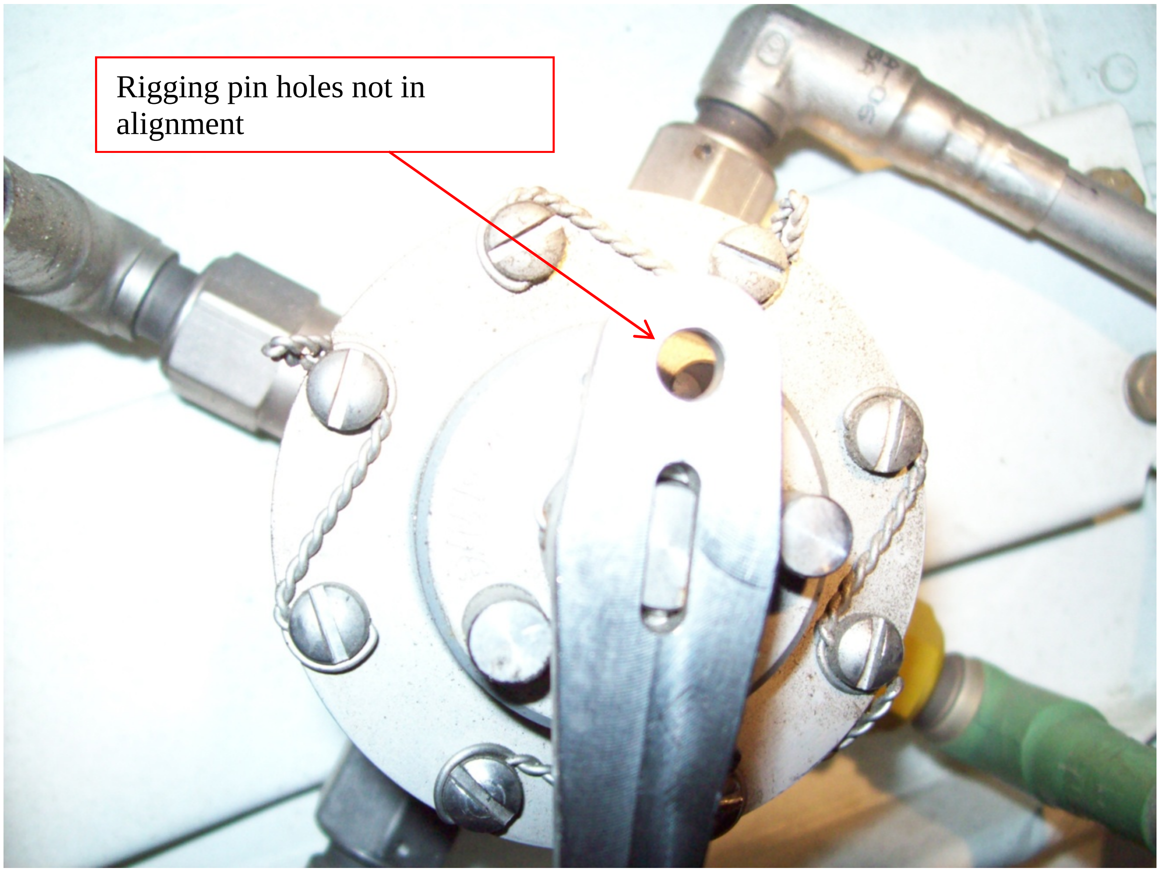

Figure 6 – Landing gear selector valve position – Photo 1

Subsequent to the pictures of the landing gear control handle and the landing gear selector valve being taken, the landing gear control handle was moved to the fullest extent of its downward travel. It was noted that the rigging pin holes were in better alignment, but still not in exact alignment. A second picture of the landing gear selector valve was taken and is included in the docket. It is reproduced in Figure 7 – Landing gear selector valve position – Photo 2.

No further checks of the landing gear selector valve were possible as the valve was removed for teardown before the details of the valve design were available and additional questions were raised.

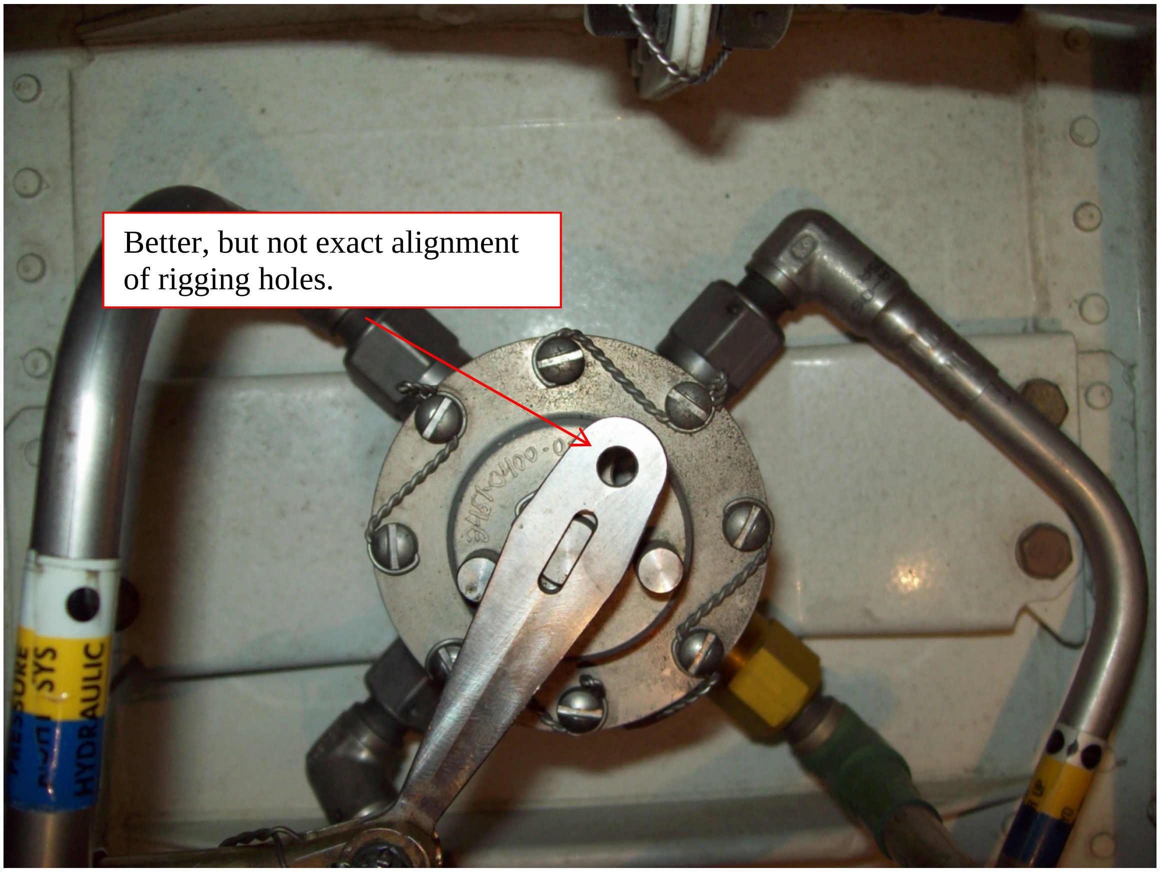

Figure 7 – Landing gear selector valve position – Photo 2

Abnormal procedure checklists

Subsequent to the incident, several abnormal procedure checklists were reviewed and modified.

Landing gear down lock indication failure checklist

The landing gear down lock indication checklist at the time of the incident contained the following steps:

3. Right Hydraulic Pressure .... CHECK
If pressure indication is normal:
4. Landing Gear Lever .... UP; MONITOR INDICATION CHANGES
After 30 seconds minimum:
5. Landing Gear Lever .... DOWN; MONITOR INDICATION CHANGES
If R HYD pressure is normal:
6. REPEAT STEPS 4 AND 5 AS NECESSARY

In essence, the procedure directs the crew to cycle the landing gear as necessary until a down and locked indication in achieved, provided the hydraulic pressure is “normal”. Normal pressure is nominally 3,000 psi. The Cockpit Voice Recorder (CVR) summary indicates the crew observed a pressure of 1,670 psi. Further, the crew did not consider 1,670 psi as “normal’ and so they terminated the checklist at that point. After reviewing the checklist post incident, GAC elected to change the language to add a new step 1 and revise the other language as follows:

1. Verify landing gear lever is at full extent of travel in the DOWN position

.
.
.

4. R hydraulic pressure ....CHECK
If pressure indication is below 1200 psi, or if all landing gears remain in the UP and LOCKED position (regardless or right hydraulic system pressure) perform EMERGENCY LANDING GEAR EXTENSION, page III-66:
5. Landing Gear Lever .... UP; MONITOR INDICATION CHANGES
After 30 seconds minimum:
6. Landing Gear Lever ....DOWN; MONITOR INDICATION CHANGES
7. Repeat steps 5 and 6 as necessary

Emergency landing gear extension checklist

The emergency landing gear extension checklist at the time of the incident contained the following steps:

3. Landing Gear Lever...DOWN
4. EMERGENCY GEAR DOWN HANDLE................RELEASE; TURN AND LIFT
5. Landing Gear .... DOWN AND LOCKED (3 DN INDICATION)

This checklist did not provide further instruction for a situation where the emergency gear extension does not achieve all three landing gear down and locked. After reviewing the checklist post incident, GAC added language to suggest a complete depressurization of the right hydraulic system by deactivating the electric motor pump and shutting down the right engine. These actions were designed to remove all pressure from the RHS, thereby eliminating any flow and pressure in the return lines which results in a pressure reduction at the retract port of the main landing gear actuator. This will aid in achieving down lock after emergency landing gear extension.

Analysis

NJA would like to offer the following analysis to the NTSB as an aid to its determination of the cause of the accident.

Analysis of landing gear selector valve position from pictures

Because the photographs of the landing gear selector valve were not taken from directly below the valve, it is not immediately clear what the angle of the valve actuating arm is relative to the 0 degree down position. However, subsequent analysis of the valve photos using photogrammetric techniques has provided good insight into the position of the valve.

The technique used is described as follows. First a known zero position is identified. From the valve drawing in Figure 3, the center of the philster head screws that secure the top plate to the valve body at the 3 and 9 o'clock positions precisely define the zero degree (down) position. By drawing a line between the centers of the heads of these two screws, a zero position is established in the photograph. Next, a second line, parallel to the first line, is drawn through the center point of the valve shaft. The center point of the valve shaft is at the same elevation as the valve actuating arm. Therefore, the second line is an accurate indication of the zero position of the arm. Finally, a third line is drawn from center of the valve shaft to the center of the rod end bolt. This line should intersect the center of the rigging pin hole at the elevation of the top of the actuating arm and defines the angle of the actuation arm.

The angle between the second and third line can then be measured with a protractor. While this is a good indication of the angle, it is not completely accurate. Because the actual angle of interest is not in the plane of the photograph, this measurement underestimates the actual angle. Further analysis could improve the measurement of the angle, but because the camera is approximately perpendicular to the valve, the remaining error is small.

Figure 6 is reproduced as Figure 8 – Landing gear selector valve position – Photo 1 w/ angles, with these lines added. Inspection of the angle between lines 2 and 3 indicates the valve is slightly more than 20.5 degrees from the 0 degree reference point for the down position. This is the angle of the landing gear selector valve actuating arm when the landing gear control handle was in the position shown in Figure 5 and prior to any movement of the landing gear control handle.

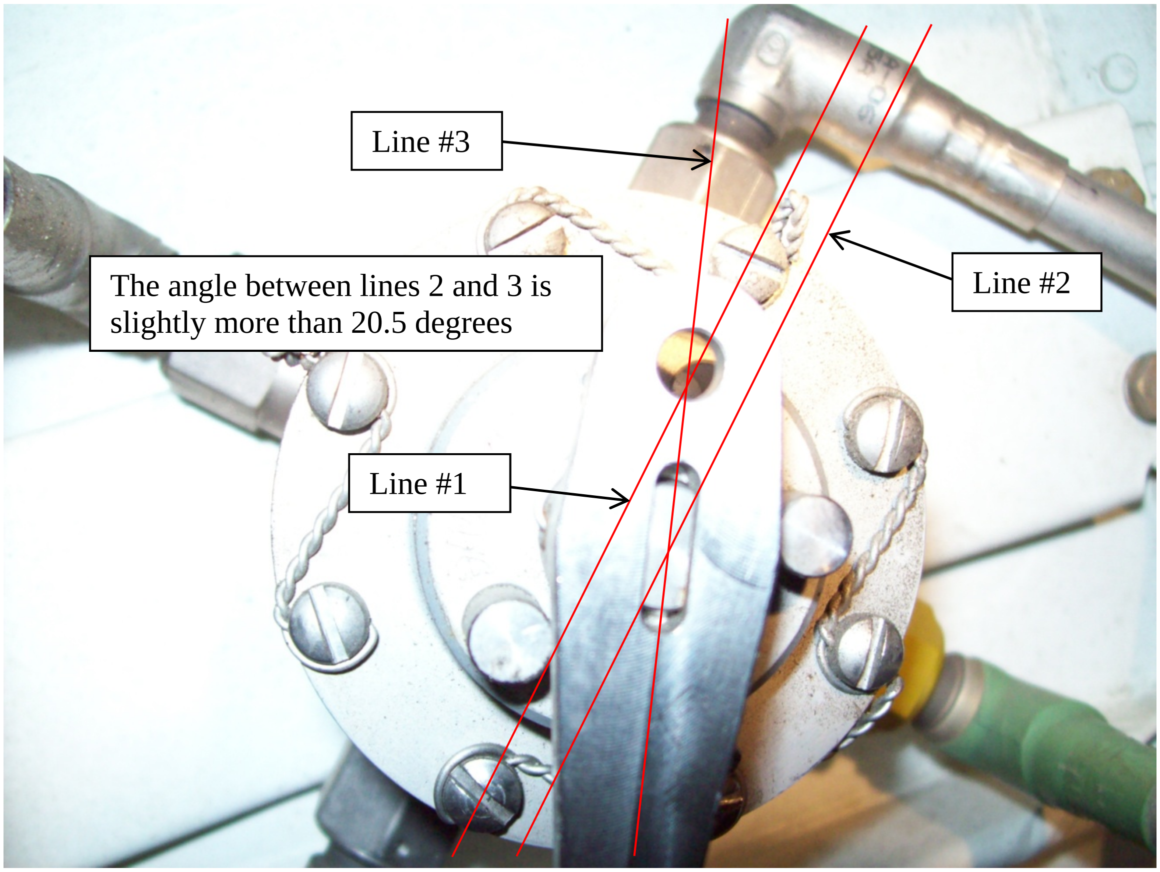

Figure 8 – Landing gear selector valve position – Photo 1 w/angles

Likewise, Figure 7 is reproduced as Figure 9 – Landing gear selector valve position – Photo 2 w/ angles, with these lines added. Inspection of the angle between lines 2 and 3 indicates the valve is slightly more than 12 degrees from the 0 degree reference point for the down position. This is the angle of the landing gear selector valve actuating arm when the landing gear control handle was at the full extent of the downward travel.

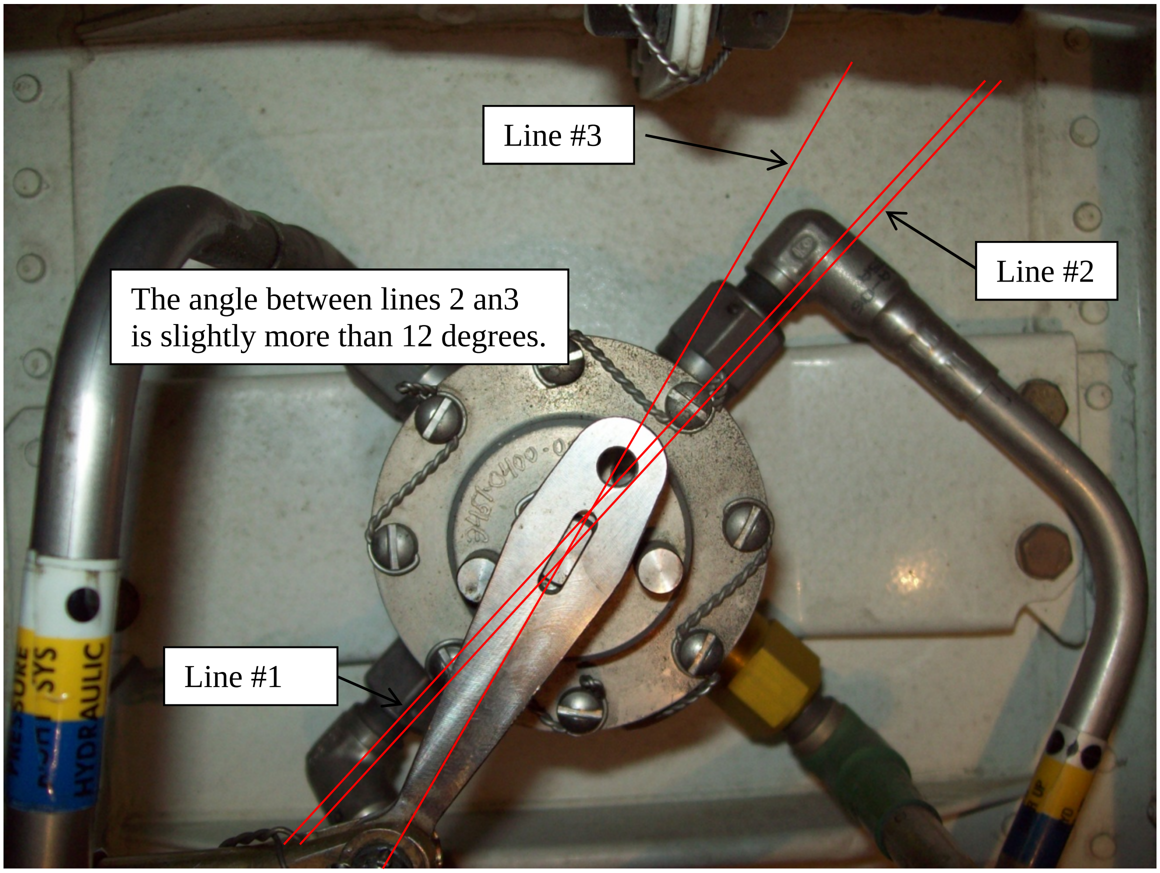

Figure 9 – Landing gear selector valve position – Photo 2 w/angles

Significance of valve positions

The analysis of Figure 9 above indicates the landing gear actuator arm position was slightly more than 12 degrees from the zero reference for the down position with the landing gear control handle at the full extent of its downward travel. The specifications for the landing gear selector valve, shown in Figure 3, require that the actuator arm be within a range of 10 to -5 to prevent interflow. Therefore, even with the landing gear control handle at the limits of its downward travel, the actuator arm was outside the specified range for no interflow. The landing gear control cable was not rigged within the design specifications.

The reason for the acceptable operation during the 20 test cycles during maintenance and the acceptable operation during the one flight between maintenance and the incident flight is that the landing gear selector valve has a large design margin. The teardown testing indicated that the actual performance of the valve is such that interflow is not initiated until the valve is at the 20 degree position, 10 degrees further that required by the specification.

Normally, the system would be quite tolerant of imprecise positioning of the landing gear control handle. When rigged within system design limits, positioning the handle so that the landing gear selector valve is anywhere from -5 to +20 degrees would result in acceptable operation of the system. With the incorrect rigging of the landing gear control cable, the acceptable range was limited to the range from 12 degrees (valve position achievable with the landing gear control handle full down) and 20 degrees (start of interflow). Therefore, the system was unreasonably sensitive to positioning of the landing gear control handle for proper operation.

The position of the landing gear selector valve post incident and prior to any movement of the landing gear control handle was found to be slightly more than 20.5 degrees. According to the teardown report for the landing gear selector valve, interflow is initiated at an angle of 20 degrees and the valve will pass 3 gpm at 20.5 degrees. The report does not provide any pressure drop measurements associated with these flow rates.

Effect of bypass flow on the hydraulic system

As discussed above, when the landing selector valve is at an intermediate position interflow or bypass flow is permitted by the valve specification. Bypass flow is fluid flow directly from the pressure port of the valve to the return port of the valve. This is not normally an issue as the valve is moved normally between the up and down positions. When the valve is moved to an intermediate position and left there, interflow can cause significant system issues.

Figure 10 – Simplified hydraulic system schematic, depicts a much simplified version of the hydraulic power system and landing gear extension/retract system.

The EDP is modeled as an ideal pressure source with associated output impedance R_s. The resistance to viscous fluid flow in the hydraulic lines is modeled by $R_{pressure\ lines}$ and $R_{return\ lines}$. By design these resistances are low. The hydraulic load is modeled by R_{load}. This represents the resistance of the hydraulic components that actually perform the design functions, such as extending the landing gear. Also noted on the figure are the points where system pressure is measured for display on the EICAS (P_{system}) and the input and return pressures as seen by the hydraulic load, $P_{load\ pressure}$ and $P_{load\ return}$ respectively. The reference for pressure measurements is P_{zero}, which represents the hydraulic reservoir pressure which is just slightly above atmospheric pressure.

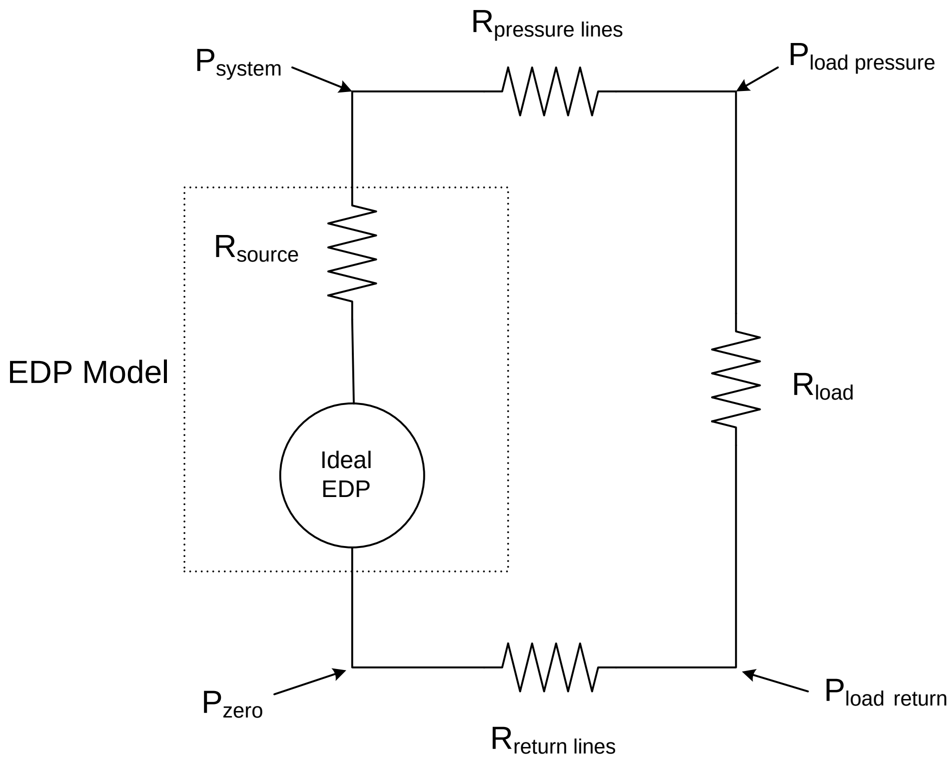

Figure 10 – Simplified hydraulic system schematic

Under quiescent hydraulic system operation, R_{load} presents a very high resistance to hydraulic flow. Typically it is only the internal leakage of the hydraulic components which is negligible. Under this condition, P_{system} and $P_{load\ pressure}$ are equal to the pressure of the ideal source (i.e. 3,000 psi), there is no pressure drop through the resistances $P_{pressure\ lines}$ and $P_{return\ lines}$, and $P_{load\ return}$ is equal to P_{zero}. As the sum of the pressure drops around the circuit must sum to zero, the entire system pressure is dropped across R_{load}.

When a hydraulic component is actuated, R_{load} is effectively decreased and fluid begins to flow. Each resistance now has an associated pressure drop across it. P_{system} is now less than the ideal source pressure and further pressure drops are present at $R_{pressure\ lines}$ and $R_{return\ lines}$. This causes $P_{load\ pressure}$ to be reduced and $P_{load\ return}$ to be increased. The pressure drop across R_{load} is less than P_{system}. Because of the fluid flow through the resistances, energy is dissipated and the fluid temperature increases. A short time later, the work of the system is complete and the system returns to its quiescent state.

When the landing gear selector valve was positioned to slightly more than 20.5 degrees during the incident flight, it resulted in a significant amount of bypass flow. This corresponds to a very low value of R_{load} and resulting high flow rates within the system. During the incident, the CVR summary indicates the system pressure displayed on the EICAS was 1,670 psi. At this pressure the EMP would not have activated and the only pressure source in the system would have been the EDP. Based on characteristics for the EDP supplied by GAC, this corresponds to a system flow rate of approximately 4.75

gpm. On order to determine the pressure on the extend and retract lines, the following assumptions were made:

- The dump valve is not yet actuated.
- $R_{pressure\ lines}$ and $R_{return\ lines}$ are about equal.
- The pressure applied to the retract and extend ports is at the midpoint of the pressure drop across R_{load}. This assumption is supported by the physical geometry of the landing gear selector valve.

Under these assumptions, the pressure on the extend and retract lines is about one half of the system pressure indicated on the EICAS or approximately 835 psi. The testing of the right main landing actuator showed that, regardless of the pressure in the extension lines, the pressure in the retraction lines must be below 280 psi in order for the main landing gear to lock down. This explains why the landing gear did not lock down upon initial landing gear extension.

Further, the high flow rates predicted by this model will result in significant heating of the hydraulic fluid. The heating effect is two fold. First, the high flow rates through the resistances result in viscous heating of the fluid. Second, the small fluid capacity relative to the flow rate results in little time for the fluid to cool in the reservoir. This explains the rapid heating of the fluid and resulting HYD OVERHEAT R CAS caution message the crew reported. This condition was reported to be a significant factor in the crew's decision making process.

Detailed retract pressure calculation

While the simple model above provides good insight into the incident, it does not explain why the emergency landing gear extension did not resolve the problem. In order to address this issue, a more detailed model of the hydraulic system is required.

Review of the schematics provides the types of components in the return line starting at the reservoir and proceeding against the direction of fluid flow to the dump valve. Application of hydraulic pressure drop models for each component and summing the pressure drops yields the pressure in the retract line. Assumptions are as follows:

- Tubing pressure drop is calculated using the Darcy-Weisbach equation under turbulent flow.
- All tubing is straight, smooth aluminum.
- Bends and fittings in tubing are accounted for using a factor of 2 applied to the predicted pressure drop.
- Flow rate is 4.75 gpm.
- Fluid properties are for Skydrol at 85 C.

The result of the calculations is shown in Table 1 – Pressure drop calculations.

Segment	Delta P (psi)	Cum. Delta P (psi)
Reservoir	25.0	25.0
Tubing - reservoir to return filter	2.5	27.5
Return filter	54.1	81.7
Tubing - return filter to restrictor relief valve	252.3	334.0

Table 1 – Pressure drop calculations

Table 1 shows that the high volume of bypass flow through the return lines from the dump valve to the hydraulic reservoir increases $P_{return\ lines}$ above the 240 psi design requirement and is above the 280 psi determined from testing the right main landing gear actuator required to achieve main landing gear down lock.

In order to further reduce pressure in the retraction lines and allow the main gear to lock down, the volume of fluid flow must be reduced. This can be accomplished by eliminating the bypass flow (i.e. repositioning the landing gear selector valve to eliminate the bypass flow). In this case, the high bypass flow was caused by improper positioning of the landing gear selector valve.

However, numerous other components, each with its own failure modes and effects, are incorporated in the RHS. A failure of other components can also cause bypass flow and high pressure in the return lines. If it is not possible for the crew to reduce the bypass flow and pressure in the return lines, shutting down the right engine is the only other alternative. Creating an emergency by shutting down an engine in flight is not an acceptable method of resolving a landing gear abnormal condition.

A simple modification to the system would be to eliminate the connection between the dump valve return port and the return lines and vent the dump valve to atmosphere or a small dedicated reservoir at atmospheric pressure. This would eliminate any dependence on return line pressures during emergency landing gear extension.

Findings

Based on the factual data contained in the public docket and the analysis contained in this document, NJA suggests the following findings for the investigation.

1) The landing gear control cable was not rigged within design specifications.
2) The landing gear extension system was unreasonably sensitive to positioning of the landing gear control handle for proper operation.
3) Upon landing gear extension, the landing gear selector valve was positioned such that high bypass flow resulted.
4) The high bypass flow prevented reduction of the pressure in the retract hydraulic lines sufficient to allow the landing gear to lock down.
5) The high bypass flow also resulted in significant heating of the hydraulic fluid and the HYD OVERHEAT R EICAS caution message.

6) Under these conditions, activation of the emergency landing gear extension system does not adequately reduce the pressure in the retraction lines to allow landing gear down lock.
7) Checklist changes suggesting shutting down the right engine to achieve main landing gear down lock is not an acceptable long term solution.

In addition, NJA suggests that the probable cause for the incident was the improper rigging of the landing gear control cable. A contributing factor was the design of the emergency landing gear extension system which did not allow sufficient reduction in return system pressure to allow main landing gear down lock.

Recommendations

NJA recommends that the NTSB issue the following recommendations as a result of this accident.

1) To the FAA and GAC – Revise the procedure for rigging the landing gear control cable to ensure that it results in the compliance with the design conditions. In particular, the landing gear selector valve should approach the mechanical stops before the landing gear control handle approaches the end of its travel. This should be confirmed in both the up and down directions.
2) To the FAA and GAC – Revise the design of the landing gear control handle to ensure that pilots feel a positive detent that accurately positions the handle in both the up and down positions.
3) To the FAA and GAC – Review the design of the emergency landing gear extension system to determine if modifications can be made to improve the reliability of the system in achieving main landing gear downlock under bypass flow conditions.