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GRAVITY PROBE B RELATIVITY MISSION

GYROSCOPE CAGING MALFUNCTION FAULT TREE ANALYSIS

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ITAR Assessment Performed **Tom Langenstein** **ITAR Control Req'd?** ☐ **Yes** ☒ **No**

Section A: Overview

During Payload Test II, Gyros 3 and 4 were found to not cage properly. Both of these gyroscopes cage off of a single circuit. Normally, signs (i.e., the caging plunger contacting with the gyro resulting in a resistance reading in the caging detector) of the gyroscope beginning to cage should start to be evident when the line is pressurized to approximately 45 psia, and Gyros 3 and 4 responded this way in room temperature test and in Payload Test I where the Dewar was at cryogenic conditions. However, in Payload Test II there was no response even up to 75 psia. This lack of caging was indicated by (1) no gyroscope motion indicated by the suspension system, and (2) no signal from the electrometer that performs a resistance check that indicates caging. The details of this testing are contained in the as-run P0520 "Gyro Caging Checkout" procedures, and the technical investigation field of DR360.

Offline qualification testing indicated that it was not necessary to cage a gyroscope for it to survive launch. Therefore the caging system was abandoned in place per PCB 477. For launch, the caging lines have been evacuated and capped.

The purpose of this document is to conduct a fault tree analysis of the caging anomaly, in order to document that the cause of the failure is properly understood. Furthermore, there is a discussion of on-orbit contingencies with each mode. In general, even when the particular failure mode was shown conclusively to have *not* occurred, the impact of that particular failure mode on the on-orbit operation of GP-B if that failure mode did occur is still discussed. This was done so as to completely span the space of all possible contingencies.

The next section summarizes the conclusion of the fault tree analysis as to the root cause of the anomaly. Section C contains some general background regarding the geometry of the caging line, which is helpful in understanding the details of the fault tree analysis. The actual fault tree is contained in tabular form in Section D. Section E is a summary discussion of on-orbit contingencies resulting from caging line failures.

Section B: Root Cause of the Anomaly

Two nodes of the fault tree remain open as possible causes of the anomaly. They are:

2.1.2.3.1 Air enters prior to probe cooldown causing single ice plug

And

2.1.2.3.2 Air enters prior to probe cooldown causing multiple ice plugs

The cases of single and multiple ice plugs were differentiated so as to discuss the different possible impacts on on-orbit operations resulting from the different plugs. As discussed in the fault tree, the case of the single plug in 2.1.2.3.1 is considered far more probable than multiple plugs based on the physics of ice plug formation in this geometry and temperature profile. However, the observed data cannot rule out multiple ice plugs, so that contingency is also discussed in detail.

The fault tree analysis concludes that air must have entered the caging circuit prior to the probe being inserted into the science mission Dewar. There were found to be two contributing factors to where this air may have entered the line. First, the caging bellows assembly, which was pumped prior to assembly, must be pumped out through a very long (>6 feet) 5-mil ID tube, leaving the potential for some air to have been left in the line. More importantly, there was a known leak in the caging circuit observed prior to the probe re-work by a negligible pressure decay during Payload Test I low temperature testing. Although its location could not be identified in room temperature testing, it is likely that it still existed (because of cleanliness concerns around the science instrument, leak checking of the line could not be done as completely as could be done in normal leak checking operations). Secondly, the probe was vented after the final room-temperature gyroscope test and the final room-temperature pump out of the caging lines so as to reinstall the VAT valves. During this time, air could leak into the caging lines.

Based on the geometry of the line (discussed in the following Section C), and experiments performed in the technical investigation of DR360, single or multiple plugs would be located at a temperature less than 20 Kelvin. It is worthwhile to note that this temperature will remain stable for the duration of the science mission, and there is practically no chance of the ice plug evaporating. However, even if it were to evaporate, the discussion in nodes 2.1.2.3.1 and 2.1.2.3.2 indicates that no gyroscope caging could occur.

Section C: Caging Line Geometry

The figure below depicts the geometry of the caging line for the Gyro 3/4 circuit. This line can be pressurized via two access points: CG1 and CG2. These two lines form the top of a "Y" which joins further down the probe. The caging circuit is single string for a length, and then it divides again at the base of the quartz block to go to Gyro 3 and Gyro 4.

The lines at the top are relatively large in diameter, roughly 3/8 of an inch. However, in order to avoid thermal acoustic oscillations in the lines, they are gradually staged down. Inside the vacuum can, the lines have a 5 mil ID.

Note that the union of the two access lines to the caging circuit occurs at a location, which is less than 20 Kelvin when the probe is inserted in the Dewar. This was done intentionally so as to assure that any air that leaked in would freeze in the section of tubing above the joint in the temperature range of about 60 to 20 degrees Kelvin and not cross contaminate from one line to the other.

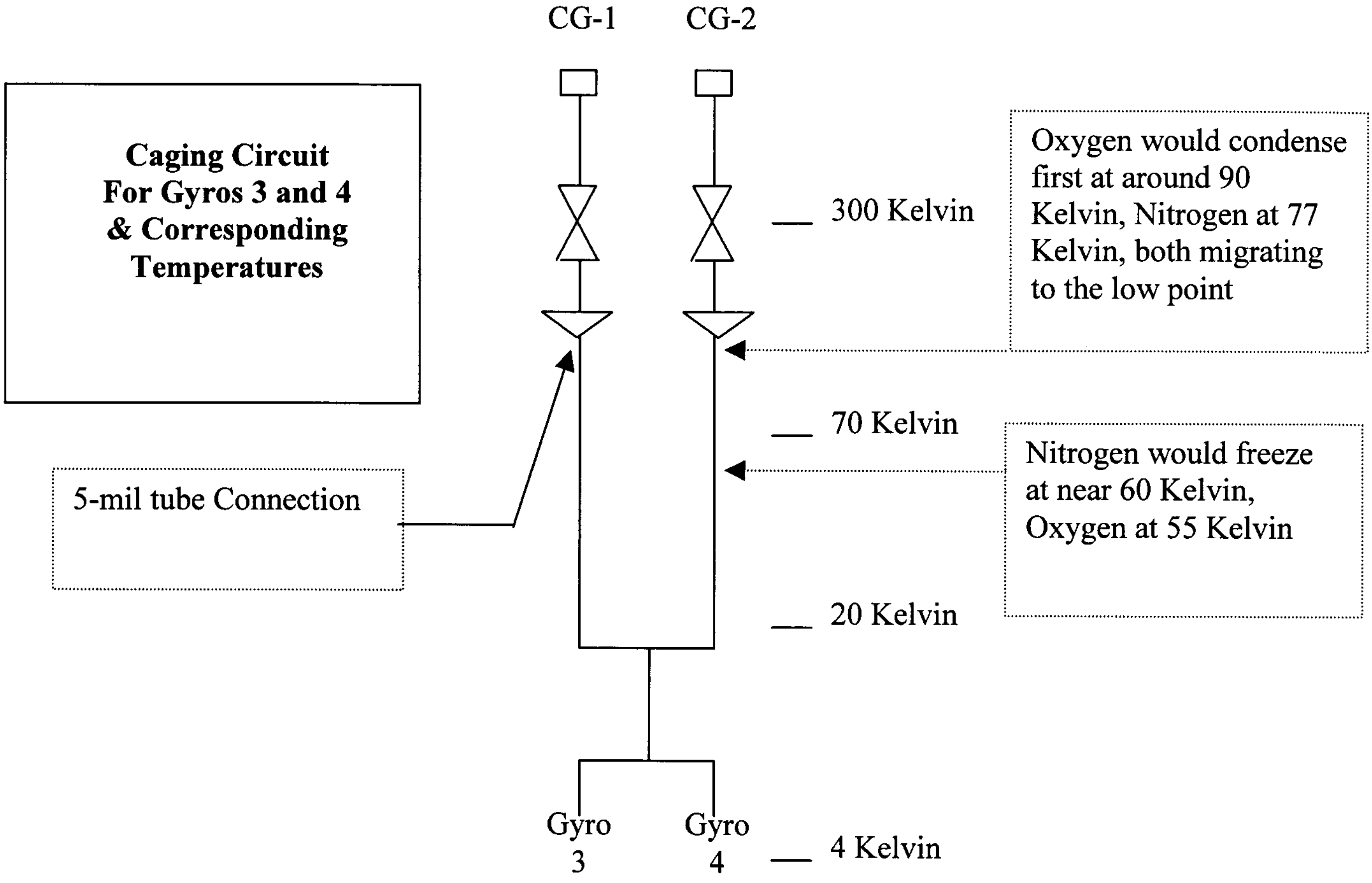


Figure 1: Caging Circuit Geometry

Section D: Gyro Caging Failure Fault Tree Analysis (Outline Form)

1. Caging Circuit is Functional

1.1 Failure to actuate gyro cage due to bad procedure or GSE

1.1.1 Gyro does not cage due to bad procedure

Investigation and Discussion: This is not a tenable failure mode. The procedure used to attempt the cage of gyros 3 and 4 (P0520) was the same used to successfully cage the other two flight gyroscopes. This procedure was also used to cage Gyros 3 and 4 during Payload Verification I. Thus it is a proven procedure. Note also that in the course of the investigation that multiple attempts were made to perform the cage, so that random operator error is also not tenable.

Closure Status: Closed

On-orbit contingency planning: None. If the failure to cage were due to a procedural error, then the caging circuit and hardware would be completely healthy. In that case, having the caging line evacuated and capped (per DR360) does not pose any additional risk. However, see Section E for a more general discussion of potential on-orbit failures.

1.1.2 Gyro does not cage due to malfunctioning GSE

1.1.2.1 Pressure gauge malfunction (line not sufficiently pressurized)

Investigation and Discussion: The same GSE used to attempt the Gyro3/4 cage also successfully caged Gyro 1 and Gyro 2. These gyros caged at nominal pressures, indicating that the gauge was reading properly. Also, in the course of the DR investigation, the line was pressurized to 60 psia, which is approximately 2 times more than should be required to observe gyroscope motion. Therefore there was sufficient margin to ensure that the cage should have occurred.

Closure Status: Closed

On-orbit contingency planning: None. If the failure to cage were due to a procedural error, then the caging circuit and hardware would be completely healthy. In that case, having the caging line evacuated and capped (per DR360) does not pose any additional risk. However, see Section E for a more general discussion of potential on-orbit failures.

1.1.2.2 Gas flow path to caging circuit does not open in GSE

Investigation and Discussion: The GSE and procedures used for the investigation were also used to successfully cage Gyros 1 and 2, indicating that the valves were functioning properly. Furthermore, DR360 indicates that, as part of the investigation, gas was introduced down one leg of the "Y", and observed to come back up the other side of the "Y". This means the caging line was clear up to the point where the two lines to that caging line unite. Therefore it is clear that the procedure and GSE succeeded in establishing the proper flow path to the caging line.

Closure Status: Closed.

On-orbit contingency planning: None. If the failure to cage were due to a procedural error, then the caging circuit and hardware would be completely healthy. In that case, having the caging line evacuated and capped (per DR360) does not pose any additional risk. However, see Section E for a more general discussion of potential on-orbit failures.

1.1.2.3 Incorrect gas used to pressurize caging circuit

Investigation and Discussion: If some gas other than Helium were used to pressurize the caging line, then it would turn to ice as it entered the cryogenic region, resulting in an ice plug. If air were to enter the line, it would turn to ice near the region of the line that is at 70 Kelvin. Referring to Section C (Caging Line Geometry), this occurs on the room-temperature side of the place where the two branches from CG1 and CG2 unite. What this means is that if the line were clogged due to incursion of air (or some other gas other than Helium) after the probe was cooled down, then it would block the path through CG1 *or* through CG2, but not both (i.e. the plug could not sit below the union of the "Y"). During the DR360 investigation, it was shown that gas could flow freely from CG1 to CG2. This could not happen if the line had become clogged from using caging gas other than Helium. Lastly, the same bottle of Helium gas was used for all caging experiments, including the successful cages of Gyros 1 and 2. Therefore it is not tenable that the incorrect gas was used to attempt the cage of Gyros 3 and 4.

Closure Status: Closed

On-orbit contingency planning: No specific on-orbit contingency planning related to this potential failure mode is necessary, since it relates only to a potential error in ground procedure that has been demonstrated to have not occurred. However, see Section E for a more general discussion of on-orbit contingency planning.

1.2 Gyro cages, but caging indicator malfunctions

Investigation and Discussion: There are two different indicators of gyroscope caging. First, the suspension system observes a change in rotor position as the caging pin starts to engage. Second, the caging pin touching the rotor, which in turn touches the gyroscope ground plane, completes a circuit that establishes a high-ohm (~100 megaohms) short between the gyroscope ground plane and probe ground. The payload was instrumented with a GSE electrometer to monitor this process, but it indicated that the cage did not occur. Both sets of GSE (the suspension system and the electrometer) were checked out, and all connections were checked multiple times. Also, independent suspension systems and electrometers were instrumented on Gyro 3 and 4. None of these 4 independent instruments indicated either Gyro 3 or 4 started to cage. Based on this redundant readout for this process, it is not credible that the gyro caged but the indicators did not function properly.

Closure Status: Closed

On-orbit contingency planning: No specific on-orbit contingency planning related to this potential failure mode is necessary, since it relates only to a potential error in ground procedure that has been demonstrated to have not occurred. However, see Section E for a more general discussion of on-orbit contingency planning.

2. Caging Circuit Does Not Function

2.1 Failure to pressurize caging bellows assembly

2.1.1 Severe caging gas leak (can not maintain pressure)

Note: A caging line would depressurize itself into different volumes depending on the precise locations of the leak and the plug, as indicated in the following sections.

2.1.1.1 Caging Line leaks into room

Investigation and Discussion: Leak checks were performed on the line, and no leak was indicated. Note that the portion of the caging line that would leak into the room remains at 300 Kelvin, and therefore is not stressed by a thermal cycle. Furthermore, during the performance of P0520 a pressure gauge was monitored, indicating that the line held the proper pressure.

Closure Status: Closed

On-orbit contingency planning: No specific on-orbit contingency planning related to this potential failure mode is necessary, since it has been demonstrated to have not occurred. However, if this type of leak did exist, it would be an air leak into the caging line, resulting in an ice plug forming in the section of caging line that is at approximately 70 Kelvin. See items 2.1.3.3.3 and 2.1.3.3.4 for a discussion of on-orbit contingencies that could result from this type of blockage.

2.1.1.2 Caging Line leaks into Well

Investigation and Discussion: An RGA monitored the well vacuum space during the performance of the caging attempt. It indicated that no significant amount of gas escaped from the caging line into the well. Furthermore, during the performance of P0520 a pressure gauge was monitored, indicating that the line held the proper pressure.

Closure Status: Closed

On-orbit contingency planning: No specific on-orbit contingency planning related to this potential failure mode is necessary, since it has been conclusively shown that this particular failure mode did not occur. Note that this failure mode does not result in an ice blockage in the line, there is simply too large of a leak in the line to maintain the caging pressure. Since both well and caging lines are to be flown in an evacuated state, the presence of the leak cannot affect on-orbit operation.

2.1.1.3 Caging Line leaks into vacuum can

Investigation and Discussion: A vacuum gauge monitored the probe vacuum space during the performance of the caging attempt. It indicated that no significant amount of gas escaped from the caging line into the probe vacuum can. Furthermore, during the performance of P0520 a pressure gauge was monitored, indicating that the line held the proper pressure.

Closure Status: Closed

On-orbit contingency planning: No specific on-orbit contingency planning related to this potential failure mode is necessary, since it has been demonstrated to have not occurred. However, see Section E for a discussion of on-orbit contingency planning relating to general failure modes.

2.1.1.4 Caging bellows assembly leak

Investigation and Discussion: A leak in the caging bellows would have manifested itself as a leak into the probe vacuum space (since the bellows resides within the vacuum can). A vacuum gauge monitored the probe vacuum space during the performance of the caging attempt. It indicated that no significant amount of gas escaped from the caging line into the probe vacuum can. Furthermore, during the performance of P0520 a pressure gauge was monitored, indicating that the line held the proper pressure.

Closure Status: Closed

On-orbit contingency planning: No specific on-orbit contingency planning related to this potential failure mode is necessary, since it has been demonstrated to have not occurred. However, see Section E for a discussion of on-orbit contingency planning relating to general failure modes.

2.1.2 Caging line blocked (gas does not reach bellows assembly)

2.1.2.1 Caging line crimped

Investigation and Discussion: A crimp in the caging line severe enough as to completely seal one side from the other would explain the data observed. However, it is extremely unlikely that this type of crimp occurred. The lines were carefully inspected prior to the vacuum can being installed. Furthermore, the caging system was fully checked out at room temperature after the vacuum can to the probe was installed. The small diameter tubes inside the probe are easily crimped, but after the vacuum can is installed they are protected. The portion of the caging lines that are outside the vacuum can (uniting the top of the vacuum can at Station 200 and the top hat of the probe) are of much larger diameter, and it would be very difficult to crimp them completely closed. Furthermore, these are protected during probe insertion into the Dewar by spacers that circumvent the probe. Thus the only place where a crimp could realistically have occurred would be inside the vacuum can, and that was completely verified at room temperature after the vacuum can was installed. Therefore this is not a tenable failure mode.

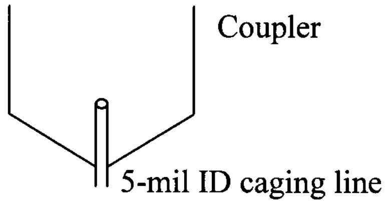
Closure Status: Closed

On-orbit contingency planning: If a crimp in the caging line had occurred, then the effect would be to block the caging actuator assembly from the caging gas, sealing it in an evacuated state. No change in on orbit conditions can result in the line becoming pressurized to >45 psia, which is what would be required for the gyroscope to begin to cage. Therefore no additional on-orbit contingency procedures are required. However, see Section E for a more general discussion on caging-related contingency procedures.

2.1.2.2 Caging line blocked by particle

Investigation and Discussion: As in 2.1.2.1, caging line blocked by particle would explain the data. However, it is extremely unlikely that this occurred. The reason lies in (1) the geometry of the caging line, (2) manufacturing checks for solder joint plugs and (3) successful room temperature functional tests. Note that the top of the caging line (at the probe top hat) is approximately 3/8" OD tubing. Given that the caging lines were treated with the same cleanliness precautions as the gyroscope spinup lines (precautions designed to keep micron-level particles out of the gyroscope), it is improbable for that portion of the line to be contaminated . However, as the line descends into the cryogenic region, it goes through a series of reductions in the size of the tubing so as to avoid thermal-acoustic oscillations in the line. By the time the line is inside the probe vacuum can, it is a 5 milli-inch ID tube. In principle, the small diameter could become clogged with particulate contamination.

However, the design of the "down-staging" of the caging line diameter is accomplished makes it highly improbable to become clogged with a particle. The system was completely assembled unclogged, which was verified in room-temperature test and the first payload test. The design is shown below. The coupler has a large ID, with the small OD caging line jutting up into the space within the coupler. Therefore, particles are not "funneled" into the 5-mil ID tube. Rather, a particle would have to land on the end of the tube and somehow migrate down in.



Gravity was taken into account in both the design and in the avoidance of contamination during manufacturing. The caging line coupler diagram above is designed so that particles falling from the top of the coupler to the 5-mil line would be funneled to the sides of the coupler. A solid particle would have fall or vent directly into the 5-mil tube, which is only 0.02% of the up-line area, in order to find its way into the 5-mil line. In addition it would have to be so small in order to fit into the line (i.e., even a perfectly circular 5-mil diameter particle would likely hit the edge of the tube and deflect to the side) that its size would not block the line. Even if such a particle did make it into the caging line, it would be extremely unlikely for it to become so firmly wedged in as to seal the line completely. Therefore this could not be the failure mode for the failure to cage Gyros 3 and 4.

Closure Status: Closed

On-orbit contingency planning: If particulate contamination had managed to seal the caging line then the effect would be to block the caging actuator assembly from the caging gas, sealing it in an evacuated state. No change in on orbit conditions can result in the line becoming pressurized to >45 psia, which is what would be required for the gyroscope to begin to cage. Therefore no additional on-orbit contingency procedures are required. However, see Section E for a more general discussion on caging-related contingency procedures.

2.1.2.3 Caging line blocked by ice

2.1.2.3.1 Air enters prior to probe cooldown causing single ice plug

Investigation and Discussion: This failure mechanism is consistent with all the data. If air were in the line prior to probe cooldown, then an ice plug would form in the portion of the line that first goes below 70 Kelvin during the probe insertion process. Based on the geometry of the probe, and the fact that the probe is cooled down by inserting it into a well full of liquid Helium, the portion of the line which first drops below 70 Kelvin is at Station 200, or roughly the top of the vacuum can. This is a portion of the line below the place where the two lines coming from CG-1 and CG-2 unite (i.e. at the base of the "Y" formed where the lines join). At this point, the actuation-gas for the caging assemblies in Gyros 3 and 4 flows through a single line. An ice block in the line at that point makes it impossible to cage either Gyro 3 or Gyro 4.

Note that since the caging assembly must be pumped out through a 5-mil ID tube, it is very easy to not pump out all of the air. Furthermore, as noted in DR360, this particular caging circuit had a known leak at low temperature into the probe vacuum space (discovered during Payload Test I). Although this leak was never identified at room temperature, the fact that the leak detector had to pump through the 5-mil tube may have compromised the quality of the leak check. After the final pumpout of the caging lines at room temperature, the probe was vented to install the VAT valves. This allowed air to enter the caging line via the leak. When the probe was inserted into the Dewar, the air solidified at Station 200, which is where the line first crosses below 70 Kelvin and where both Gyros 3 and 4 are fed through a single caging line.

Since gas will tend to condense at the coldest portion of the line, which is located at Station 200 during probe insertion, there is a strong tendency for the line to form an ice block in a single place. This makes this failure mode more likely than the multiple ice block fault discussed in 2.1.2.3.2. However, based strictly on the observable data, it is impossible to differentiate between this single ice block mode and the multiple block failure mode given in 2.1.2.3.2.

Closure Status: Open – Probable Failure Mode

On-orbit contingency planning: Since the ice block is located near Station 200, it is sufficiently cold that it is highly unlikely that the ice block will warm up over the course of the mission. This means that the block will not move or disappear during the course of the science mission. Note that even in the unlikely worst-case scenario where the ice plug sublimates completely, the gyroscope still will not cage. By definition, this line contains at most 14.7 psia equivalent of air, and at least 30 psia is necessary to begin to cage the rotor. Therefore even if all the ice were to evaporate, the line still would not be sufficiently pressurized so as to cage the gyroscope.

2.1.2.3.2 Air enters prior to probe cooldown causing multiple ice plugs

Investigation and Discussion: This is similar to 2.1.2.3.1, except that the air that encroached into the caging line formed multiple ice blocks. At the time the probe is cooled down, all of the air in the line should form at the location that first falls below 70 Kelvin. Since during probe insertion this occurs at a single place (Station 200), it is very unlikely that multiple blockages will form. However, it cannot be conclusively disproved, and therefore this must still be listed as a possible failure mode.

Closure Status: Open – Possible Failure Mode

On-orbit contingency planning: The concern for this type of failure lies in the potential for high-pressure helium to have become trapped between the two plugs. As noted in 2.1.2.3.1, it is not possible for gas coming from a single plug to cause the caging system to actuate. This is because (1) the plug is in a location which will remain below 20 Kelvin for the duration of the science mission, making evaporation of the plug highly improbable, and (2) even if the plug did evaporate, by definition there would only be sufficient Helium gas to pressurize the line to 14.7 psia, which is roughly a factor of 2 less than is required to cause the gyro to cage.

However, if there were two ice blocks, then conceivably the high-pressure gas that was used to attempt to cage the gyroscope during the DR360 investigation could have become lodged between the two ice plugs. It should be noted that this is extremely unlikely, as it would require (1) an initial partial blockage of the first plug, allowing gas to get past it, and (2) a complete blockage of the second plug, so that the gas could not cage, then (3) the first plug sealing off so that the gas could not escape, even when pumped on over night, and finally (4) the second block to unseal itself, allowing the gyroscope to cage from the high-pressure gas.

Based on the geometry of the caging line the plug should have formed in the 5-mil ID line. The greater the distance in this line between the two plugs, the larger the reservoir of high-pressure helium, yielding a worst-case scenario. Taking a maximum distance between the two plugs to be 3 ft, (which is very unlikely, as all the ice will initially form at Station 200 when the probe cools down because it is the location where the line first contacts the liquid Helium), the maximum volume for this reservoir in the line is L*πR^2 = 0.012 cc (0.0007 in^3). Estimating an additional 6 ft of caging line after the second plug (after the line enters the vacuum can, it has to go to the bottom of the quartz block, split into two different branches, then come back up to gyros 3 and 4), and also counting a 2 cc (0.12 in^3) volume total for the two caging bellows assemblies (estimated from the drawing), there is a total volume of 2.023 cc (0.123 in^3) on the gyro side of the second plug.

According to DR360, the maximum pressure this line was exposed to was 60 psia. If V1 is the volume between the two ice plugs (0.0007 in^3), and V2 is the volume on the gyro side of the two plugs (0.123 in^3), then if the second plug starts to leak, allowing the high pressure gas to enter the caging assemblies, the highest pressure that the caging assembly can reach is given by the ratio of the two volumes: P2 = P1*V1 / (V1 + V2) = 0.34 psia. This is insufficient pressure to cage the gyroscope, with a safety factor of almost 88 in pressure before the caging assembly would interfere with gyro motion.

Note that this was an extremely unlikely failure scenario to begin with. But even if it were to occur, there would be no negative impact on the science mission. Therefore it is not necessary to develop specific on-orbit contingency procedures related to this particular failure mode. However, see Section E for a general description of caging failure modes and on-orbit operations.

2.1.3.3.3 Air enters probe after cooldown causing single ice plug

Investigation and Discussion: If air were to enter the probe after the probe is cooled down (e.g. because a valve is slowly leaking), the incoming air would migrate down the caging line, solidifying when the temperature drops below 70 Kelvin. As discussed in Section C, there are two access points to the Gyro 3/4 caging line, which unite further down the probe forming a "Y". When the probe is installed in the Dewar, the lines have already reached approximately 20 Kelvin at the point where the two lines unite. Therefore, if air were to enter the line after probe cooldown, it would form ice above the union of the two lines. Since the DR360 technical investigation determined that the lines are unblocked above this union (by flowing gas from one branch to the other), the ice plug could not have formed after the probe cooled down.

Closure Status: Closed

On-orbit contingency planning: This failure mode has been shown to have not occurred, based on the fact that the caging lines have no obstruction down to at least 20 Kelvin. However, if it were to occur, then the plug would be sitting at the thermal boundary of where air ice can form, meaning that it would be feasible for it to warm up during the course of the science mission. Depending on how much air had entered the line, it is possible for an undesired cage to occur. Again, experiments show that there is no plug near the thermal boundary. Even so, for the sake of completeness this scenario is examined further with respect to on-orbit contingency planning in Section E.

2.1.3.3.4 Air enters probe after cooldown causing multiple ice plugs

Investigation and Discussion: If air were to enter the probe after the probe is cooled down (e.g. because a valve is slowly leaking), the incoming air would migrate down the caging line, solidifying when the temperature drops below 70 Kelvin. As discussed in Section C, there are two access points to the Gyro 3/4 caging line, which unite further down the probe forming a "Y". When the probe is installed in the Dewar, the lines have already reached approximately 20 Kelvin at the point where the two lines unite. Therefore, if air were to enter the line after probe cooldown, it would form ice above the union of the two lines. Since the DR360 technical investigation determined that the lines are unblocked above this union (by flowing gas from one branch to the other), even a single ice plug could not have formed after the probe cooled down. Therefore multiple plugs could also not have formed.

Closure Status: Closed

On-orbit contingency planning: If this failure mode were to occur, the impact would be the same as for 2.1.3.3.3 (single ice plug in the line). See that section for more details.

2.2 Mechanical malfunction of caging actuator assembly

2.2.1 Caging pin detached from bellows

Investigation and Discussion: If the caging pin were to become debonded from the caging bellows assembly, the rotor would not have passed its freedom of motion tests during its checkout. This is because that pin is constrained to fall into the caging hole in the gyroscope housing, which is the only place for it to go if it separates from the caging bellows. Since both Gyros 3 and 4 passed their freedom of motion and spin tests, the caging pin must still be attached to the bellows. It is also worthwhile to note that the caging assemblies for both Gyros 3 and 4 had been thermal cycled at least once during acceptance testing, and an additional time during Payload Test I, before the final thermal cycle into Payload Test II. Therefore it is very unlikely that both Gyro 3's and Gyro 4's caging assembly would have suddenly failed from a mechanical point of view in the final thermal cycle.

Closure Status: Closed

On-orbit contingency planning: This failure mode has been shown to have not occurred. However, if it were to occur the caging pin would interfere with gyroscope freedom of motion on orbit. The gyroscope would not pass its on-orbit tests prior to the final spin sequence. Therefore the gyroscope would never be spun to full spin speed, and glean useful science data. Note that the caging pin essentially becomes contamination in the gyroscope housing, and the indicators and contingency procedures for this failure are identical to those for any on-orbit gyroscope contamination.

2.2.2 Mechanical obstruction does not permit caging pin motion

Investigation and Discussion: The caging assembly is held firmly in place against the gyroscope housing by the gyroscope retention hardware. This is installed, inspected, and functionally checked out prior to vacuum can installation. After vacuum-can installation it is re-verified. Note that the Gyro 3 caging assembly was successfully tested at low temperature as part of Payload Test I, and no change was made to that installation during the probe recycle. Although the Gyro 4 caging assembly was removed and reinstalled during the probe recycle, it was thoroughly inspected and checked out prior to inserting the probe in the Dewar. There is no way for the assembly to be sufficiently out of alignment for the gyroscope to not cage, and in any case as stated above that alignment was verified multiple times. Finally, even if something were to suddenly change so as to mechanically constrain one caging pin, it is extremely unlikely that this could occur in both caging assemblies simultaneously. This is not a tenable mechanism for the failure observed.

Closure Status: Closed

On-orbit contingency planning: This failure mode has been shown to not have occurred, but if it had there would still be no impact on on-orbit operations. Because the caging pin never entered the gyroscope cavity, the gyroscope would still function as designed. In principle, a pressurized caging assembly does apply a force on the gyroscope housing, attempting to move it out of alignment. But the caging line was evacuated prior to launch, and furthermore the gyroscope retention hardware was designed to keep the gyroscope correctly positioned with adequate margins of safety even for a full 180 psi cage. Since the maximum pressure this line was exposed to was 60 psi, there would clearly still be abundant margin to keep this from moving the gyroscope.

Section E: On-orbit Contingency Summary

As discussed in Section A, the caging lines were evacuated and capped for flight. The natural concern, which occurs when an ice plug has been diagnosed, is that the ice plug might evaporate due to temperature changes in the system, causing an undesired cage of the gyroscopes. In every node of the fault tree, it was shown that this would not occur. The technical investigation documented in DR360 shows that the plug is at a temperature less than 20 Kelvin. This cannot rise to the necessary 70 Kelvin during all ground and on-orbit operations. If such a radical temperature change were to occur, it would mean the gyroscopes, SQUIDs, and lead bag would cease to superconduct long before the plug would evaporate. Furthermore, based on the fault observed, there is not sufficient gas iced in the line to cause an undesired cage.

Even so, it is worthwhile considering that eventuality. In this case, the caging pin acts like contamination in the housing, interfering with free motion of the gyroscope. It would be indistinguishable on orbit from any other form of gyroscope housing contamination. The indicator on orbit is that the gyroscope would not pass its freedom of motion and spin tests. In this event, the gyroscope would not be spun to the nominal science frequency, and no useful science data could be obtained from the affected gyroscope.

If an undesired cage were to occur after the gyroscope has been spun up, then the gyroscope will most likely suffer structural damage to the housing. However, the suspension systems have been designed so as to be able to maintain gyroscope levitation of the other gyroscopes even in the event of a seismic disturbance caused by delevitation of a spinning gyroscope. Again, this failure could occur due to any kind of gyroscope contamination, and it is impossible on orbit to distinguish between particulate contamination and encroachment of the caging pin.

Contamination of the gyroscope on orbit has been identified as a program risk (Risk ID: Mulfelder-10). Progress in the mitigation of this risk is tracked at every monthly review. Most recently, the program has added a person to work the mission operations contingencies that would result from a malfunctioning gyroscope on orbit.

It should be stressed that the fault tree analysis contained in this document does not find a credible failure in which the gyroscope inadvertently cages on orbit. The preceding discussion was included so as to document the impact of all conceivable contingencies.

Section F: Summary

A complete fault tree analysis was performed on the caging anomaly. The root cause was found to be an ice plug in the line, formed by air that entered the line prior to the probe's insertion into the flight dewar. It was further found that the plug would remain stable throughout the science mission, and there is no credible mechanism for an inadvertent caging of the gyroscope. On-orbit contingencies were also addressed for each of the nodes in the fault tree.

Section G: Fault Tree Block Diagram