**Hazard Analysis Table (J. Novak, 11-10-01, updated by M. Snow, 8-15-03)**

## n-p-d-Gamma LH2 TARGET – FAILURE ANALYSIS

## TABLE 1 –FAILURE ANALYSIS RESULTS SUMMARY

**NOTES**

This Failure Analysis describes the hazards to Experiment Workers at LANSCE from failures of experimental components. The hazards to Co-Located Workers (workers in adjacent experiments and other people inside ER2) will be substantially less than hazards to Experiment Workers. There is no hazard to the general public outside the TA-53 boundary.

**LIKELIHOOD LEVELS:**

**I** **Frequent/Expected** Likely to occur often during the life of the experiment. "Happened to you many times." Expected once in 1-10 tries -or- $>10^0$ /yr.

**II** **Probable/Likely** Likely to occur several times during the life of the experiment. "Happened to you once." Expected once in 10-100 tries -or- $<10^0$ /yr. to $>10^{-2}$ /yr.

**III** **Occasional/Unlikely** Should not occur during the life of the experiment. "Was a near-miss to you." Expected once in $10^2$-$10^4$ tries -or- $<10^{-2}$ /yr. to $>10^{-4}$ /yr.

**IV** **Improbable/Extremely unlikely** Unlikely but possible to occur during the life of the experiment. "Happened once to someone you know." Expected once in $10^4$-$10^6$ tries -or- <10-4 /yr. to $>10^{-6}$ /yr.

**V** **Remote/Beyond extremely unlikely** Should not occur during the life of the experiment. "Happened once, long ago, at another facility." Expected once in $10^6$-$10^8$ tries -or- $<10^{-6}$ /yr.

**CONSEQUENCE SEVERITY LEVELS**

**A** **Catastrophic**

*Health*: Immediate health effects. Death, coma, loss of limb, loss of sight – "H-A"

*Experiment:* Experiment cancelled. – "E-A"

**B** **Critical**

*Health:* Long-term health effects, disability, or severe injury -- non-life threatening. Broken bones, bad cuts, 3rd degree burns, unconsciousness, out of work 1 week to 1 month. – "H-B"

*Experiment:* Experiment loses 1 run cycle. – "E-B"

**C** **Moderate**

*Health:* Lost-time injury, work restrictions but no disability. 2nd degree burns, out of work 1 day to 1 week, work restrictions up to 1 week. – "H-C"

*Experiment:* Experiment loses 1 week. – "E-C"

**D** **Minor**

*Health:* Lost-time injury but no disability or work restrictions. – "H-D"

*Experiment:* Experiment loses 1 day. – "E-D"

**E** **No measurable consequences** – "H-E, E-E"

**RISK MATRIX -- EXPERIMENT WORKER (EW) and EXPERIMENT (E)**

An Experiment Worker is a person inside the general NPDGamma experiment area.

| | **I** | **II** | **III** | **IV** | **V** |
|---|---|---|---|---|---|
| **A** | 1 | 1 | 2 | 2 | 3 |
| **B** | 1 | 1 | 2 | 3 | 4 |
| **C** | 1 | 2 | 3 | 4 | 4 |
| **D** | 2 | 3 | 4 | 4 | 4 |
| **E** | 4 | 4 | 4 | 4 | 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| **A** | **COMPONENT RUPTURES** | | | | | | | | | |
| 1 a | LH2<br>Target flask or piping inside vacuum vessel | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel, piping, pumping system components, and flask. Assume vacuum vessel, piping, or pumping system components *do not* rupture.<br>Note: H2 release to air if vacuum vessel or system components rupture. See Item A.1b. | **III** | **H-E**<br>**E-B** | Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Verify design with independent FEA analysis.<br>Fabricate and test per approved QA Plan (e.g., use certified materials, use certified welders, radiograph welds, pressure test final assembly, etc.)<br>Design vacuum vessel, piping, pumping system components, and relief system for full rupture of LH2 vessel.<br>Fabricate and test vacuum vessel per approved QA Plan | **V** | **H-E**<br>**E-B** | EW – 4<br>E -- 2 | EW – 4<br>E -- 4 |
| 1 b | LH2<br>Target flask or piping inside vacuum vessel | Rupture -- due to material failure, weld or fabrication failure, or design failure | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel and flask. Assume vacuum vessel *ruptures*. | **IV** | **H-A**<br>**E-A** | Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Verify design with independent FEA analysis. | **V** | **H-E**<br>**E-B** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | (e.g., over-stress) | | | | Fabricate and test per approved QA Plan<br>Design vacuum vessel, piping, pumping system components, and relief system for full rupture of LH2 vessel.<br>*Fabricate and test vacuum vessel per approved QA Plan.* Surround main vacuum weld joints and oring seals with helium gas. Design relief system for full LH2 vessel rupture. Build to approved QA Plan. | | | | |
| 1c | LH2<br>Target flask or piping inside vacuum vessel | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel and flask. Assume vacuum vessel *ruptures*, and helium jacketing *ruptures*. H2 released to exp't. cave.<br>End of exp't. | **V** | **H-A**<br>**E-A** | Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Verify design with independent FEA analysis.<br>Fabricate and test per approved QA Plan<br>Design vacuum vessel, piping, pumping system components, and relief system for full rupture of LH2 vessel.<br>Fabricate and test | **V** | **H-A**<br>**E-A** | EW – 3<br>E -- 3 | EW – 3<br>E -- 3 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | | | | vacuum vessel per approved QA Plan.<br>Surround main vacuum wled joints and oring seals with helium gas. Design for full LH2 vessel rupture. Build to approved QA Plan. | | | | |
| 2 a | LH2<br>Target flask or piping inside vacuum vessel | Rupture due to overpressure (inadequate relief capacity) | $LH_2$ released to vacuum vessel. Rapid pressure rise in vacuum vessel. Assume vacuum vessel does not rupture. | **III** | **H-E**<br>**E-B** | See Item A.1a.<br>In addition: --<br>Design LH2 and main vacuum vent lines and relief valve capacities carefully for max. credible heat load. Conduct test measurements with liquid nitrogen and use approved methods for extrapolating to liquid hydrogen. | **V** | **H-E**<br>**E-B** | EW – 4<br>E -- 2 | EW – 4<br>E -- 4 |
| 2 b | LH2<br>Target flask or piping inside vacuum vessel | Rupture due to overpressure (inadequate relief capacity) | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel and flask. Assume internal vacuum windows and/or internal weld jointsrupture, but helium jacketing is not | **IV** | **H-E**<br>**E-B** | See Item A.1b.<br>Design LH2 and main vacuum vent lines and relief valve capacities carefully for max. credible heat load. Conduct test measurements with liquid nitrogen and use approved methods for | **V** | **H-E**<br>**E-B** | EW – 4<br>E -- 3 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | breached. | | | extrapolating to liquid hydrogen. | | | | |
| 3 a | LH2<br>Target flask or piping *outside* vacuum vessel but *inside* cave | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | LH2 release to experiment cave<br>End of experiment. | **III** | **H-A**<br>**E-A** | See A.1c.<br>Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Fabricate and test per approved QA Plan (e.g., use certified materials, use certified welders, radiograph welds, pressure test final assembly, etc.) Design helium jacketing to prevent weld joint and o-ring seal contact with atmosphere. Design LH2 and main vacuum vent lines and relief valve capacities carefully for max. credible heat load. Conduct test measurements with liquid nitrogen and use approved methods for extrapolating to liquid hydrogen. Build to approved QA Plan. | **V** | **H-E**<br>**E-B** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |
| 3 b | LH2<br>Target flask or piping | Rupture due to overpress | LH2 release to experiment cave<br>End of | **III** | **H-A**<br>**E-A** | See Item A.1c.<br>In addition: -- | **V** | **H-E**<br>**E-B** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | *outside* vacuum vessel but *inside* cave | ure (inadequate relief capacity) | experiment. | | | Design LH2 and main vacuum vent lines and relief valve capacities carefully for max. credible heat load. Conduct test measurements with liquid nitrogen and use approved methods for extrapolating to liquid hydrogen. | | | | |
| 4 a | Vacuum jacket<br>Main vacuum vessel, vacuum pumping system, and all vacuum piping | Rupture -- due to material failure, weld or fabrication failure, or design failure. | If helium jacketing were not present, air floods vacuum space giving high heat load on $LH_2$ flask.<br>Assume LH2 flask *does not* rupture. | **III** | **H-E**<br>**E-B** | See Items C.2.<br>Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Verify design with independent FEA analysis.<br>Fabricate and test vacuum vessel per approved QA Plan (e.g., use certified materials, use certified welders, radiograph welds, pressure test final assembly, etc.)<br>Enclose weld joints and o-ring seal areas inside cave in helium jacketing | **V** | **H-E**<br>**E-B** | EW – 4<br>E -- 2 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | | | | so that vacuum space will be filled with helium, not air. Build to approved QA Plan.<br><br>Design LH2 and main vacuum vent lines and relief valve capacities carefully for max. credible heat load. Conduct test measurements with liquid nitrogen and use approved methods for extrapolating to liquid hydrogen.<br><br>For piping outside cave build from very strong, reliable components (e.g., all welded components, VCR fittings, etc.). Provide mechanical guards to protect from damage. | | | | |
| 4 b | Vacuum jacket<br>Main vacuum vessel, vacuum pumping system, and | Rupture -- due to material failure, weld or fabrication failure, or design | Air, assuming that He Jacket is not present, floods vacuum space; high heat load on $LH_2$ flask.<br>Assume LH2 | **IV** | **H-B**<br>**E-B**<br>**H-A**<br>**E-A** if H2/air mixture in vacuum space or cave explodes | See Items C.2.<br>Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Verify design with independent FEA | **V** | **H-E**<br>**E-B** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | all vacuum piping | failure. | flask *ruptures*.<br>If $H_2$ vessel ruptures, have air/$H_2$ mixture in vacuum space; see Contaminants Section<br>Possible H2 release to cave. | | | analysis.<br>Fabricate and test vacuum jacket per approved QA Plan (e.g., use certified materials, use certified welders, radiograph welds, pressure test final assembly, etc.)<br>Fabricate and test vacuum vessel per approved QA Plan.<br>Enclose weld joints and o-ring seals inside cave in helium jacket so that vacuum space will be filled with helium, not air.. Build to approved QA Plan.<br>For piping outside cave that is difficult to enclose in helium jacketing, build from very strong, reliable components (e.g., all welded components, VCR fittings, etc.). Provide mechanical guards to protect from damage.<br><br>Design LH2 and main vacuum vent lines and relief valve capacities carefully for max. | | | | |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | | | | credible heat load. Conduct test measurements with liquid nitrogen and use approved methods for extrapolating to liquid hydrogen. | | | | |
| 5 | Vacuum jacket Main vacuum vessel, vacuum piping | Rupture – due to external pressure (from helium jacketing) | He floods insulating space; high heat load on $LH_2$ flask. | **III** | **H-E**<br>**E-B** | See Item A.4.<br>In addition: --<br>Design vacuum jacket for appropriate external pressure.<br>Design helium jacketing pressure control and relief system appropriately to avoid high external pressures. | **V** | **H-E**<br>**E-B** | EW – 4<br>E -- 2 | EW – 4<br>E -- 4 |
| 6 | Vacuum jacket Main vacuum vessel and piping | Rupture – due to internal pressure (e.g., when $LH_2$ flask ruptures) | $LH_2$ release to helium jacketing. Rapid pressure rise in helium lines Assume helium lines does not rupture. | **III** | **H-E**<br>**E-B** | See Items A.1, A.2. | **V** | **H-E**<br>**E-B** | EW – 4<br>E -- 2 | EW – 4<br>E -- 4 |
| 7 | LH2<br>Helium jacketing and associated | Rupture -- due to material failure, weld or | Helium release to cave. | **III** | **H-C**<br>**E-B** | Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals. | **V** | **H-C**<br>**E-B** | EW – 3<br>E -- 2 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | piping | fabrication failure, or design failure (e.g., over-stress) | | | | Verify design with independent FEA analysis.<br>Fabricate and test per approved QA Plan (e.g., use certified materials, use certified welders, radiograph welds, pressure test final assembly, etc.) | | | | |
| 8 | LH2<br>Helium jacketing and associated piping | Rupture due to overpressure (inadequate relief capacity) | Helium release to cave. | **III** | **H-C**<br>**E-B** | See Item A.7<br>In addition: --<br>*Design for full LH2 vessel rupture. Build to approved QA Plan.* | **V** | **H-C**<br>**E-B** | EW – 3<br>E -- 2 | EW – 4<br>E -- 4 |
| **B** | **COMPONENT FAILURES** | | | | | | | | | |
| 1 | REFRIG-ERATOR<br>Any | Cooling failure (either device or power failure) | $H_2$ pressure rises slowly. Heat load on LH2 is much lower than maximum credible failure. Relief valves open. No safety problems, only operational problems. | **III** | **H-E**<br>**E-C** | | **IV** | **H-E**<br>**E-D** | EW – 4<br>E -- 3 | EW – 4<br>E -- 4 |
| 2 | REFRIG-ERATOR<br>Temperature controller | Fails low | $LH_2$ freezes. Possible line plugging with frozen hydrogen. | **III** | **H-E**<br>**E-C** | Interlock target pressure and temperature sensors to alarm.<br>Surround $H_2$ system inside cave with helium | **IV** | **H-E**<br>**E-D** | EW – 4<br>E -- 3 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | Possible reduction of $H_2$ gas pressure below atmospheric, with increased risk of drawing in air/contaminants. | | | jacketing.<br>Design all H2 system to be vacuum-tight. Build and test per approved QA Plan. | | | | |
| 3 | REFRIG-ERATOR<br>Temperature controller | Fails high | Inadequate cooling. If refrigerator is ON, gives extra heat load on $LH_2$ system.<br>If refrigerator is OFF, could cause very hot local spot in piping, possibly weakening piping, damaging heater, or causing electrical short to ground. | **III** | **H-E**<br>**E-B** | Interlock temperature controller to refrigerator operation and/or flask temperature. | **IV** | **H-E**<br>**E-D** | EW – 4<br>E -- 2 | EW – 4<br>E -- 4 |
| 4 | $LH_2$ flask<br>Relief valve(s) | Fails to open or opens only partially | High pressure in $LH_2$ flask. Possible rupture.<br>$LH_2$ release to vacuum jacket Rapid pressure | **IV** | **H-E**<br>**E-C** if helium jacketing or vacuum piping do not rupture<br>**H-A** | Use ASME code relief valves or devices with equal reliability.<br>Use redundant relief valves.<br>Design vacuum vessel, | **V** | **H-E**<br>**E-D** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | rise in vacuum jacket, with possible overpressure rupture | | **E-A** if $H_2$ is released to cave<br>**H-B, E-B** if $H_2$ is released outside cave | piping, pumping system components, and relief system for full rupture of LH2 vessel.<br>See Items A.1, A.2, A.3 | | | | |
| 5 | Vacuum jacket Relief valve(s) | Fails to open or opens only partially | High pressure in vacuum jacket. Possible rupture.<br>$H_2$ release to helium jacketing (if vacuum jacket ruptures) or to air (if vacuum piping or pumping system rupture), if gas source is $LH_2$ flask failure.<br>Rapid pressure rise in helium jacket, with possible overpressure rupture | **IV** | **H-E, E-C** if helium jacketingor vacuum piping do not rupture<br>**H-A, E-A** if $H_2$ is released to cave<br>**H-B, E-B** if $H_2$ is released outside cave | Use ASME code relief valves or devices with equal reliability.<br>Use redundant relief valves.<br>Design helium jacket relief system appropriately for vacuum jacket rupture<br>See Items A.4, A.5, A.6 | **V** | **H-E**<br>**E-D** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |
| 6 | Helium jacketing<br>Relief valve(s) | Fails to open or opens only partially | High pressure in helium jacketing. Possible rupture. Possible damage to or collapse of vacuum jacket if source of gas is He supply | **IV** | **H-E**<br>**E-C** if helium jacket does not rupture<br>**H-A, E-B** if $H_2$ is released to cave<br>**H-C**<br>**E-C** if He is | Use ASME code relief valves or devices with equal reliability.<br>Use redundant relief valves.<br>Design helium jacketing relief system appropriately for vacuum jacket rupture or He | **V** | **H-E**<br>**E-D** | EW – 2<br>E -- 3 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | failure.<br>$H_2$ release to cave air if He jacket ruptures and gas source is $LH_2$ flask failure.<br><br>He released to cave air if source is He supply gas failure. | | released to cave | supply system failure.<br>See Section A. | | | | |
| 7 | Vacuum jacket Vessel or piping | Damage/rupture from shrapnel created by rupture of the $LH_2$ flask | See items on rupture of vacuum jacket from other causes.<br>$LH_2$ released to cave IF helium jacketing also ruptures | **IV** | **H-E, E-C** if helium jacket stays intact.<br>**H-A, E-B** if helium jacket ruptures | Use ductile materials for all vessels at all temperatures.<br>Design to ASME code. | **V** | **H-E**<br>**E-D** | EW – 2<br>E -- 3 | EW – 4<br>E -- 4 |
| 8 | Helium jacketing Vessel or piping | Damage/rupture from shrapnel created by rupture of the vessel inside | $LH_2$ release to cave<br>See Items on rupture of vacuum jacketing from other causes. | **IV** | **H-A, E-B** | Use ductile materials for all vessels at all temperatures.<br>Design to ASME code. | **V** | **H-E**<br>**E-D** | EW – 2<br>E -- 3 | EW – 4<br>E -- 4 |
| 9 | $H_2$ gas handling system | Broken or leaking | $H_2$ release into ER2<br>Air/H2 mixture | **III** | **H-D, E-D** if leaking<br>**H-C, E-C** if | Build from very strong, reliable components (e.g., all welded | **IV** | **H-E**<br>**E-D** | EW – 3<br>E -- 3 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | Pipes outside cave | | inside H2 gas system. | | broken | components, VCR fittings, etc.).<br>Protect all pipes from mechanical damage. | | | | |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| **C** | CONTAMINANTS | | | | | | | | | |
| 1 | $LH_2$<br>Target flask or piping inside the vacuum jacket. | Plugged vent line -- due to freezing of contaminants in H2. | Rupture – due to overpressure<br>$LH_2$ release to vacuum vessel. Rapid pressure rise in vacuum vessel | **III** | **H-E**<br>**E-B**. | *See item A.2, A.3, A.4, A*<br>Clean feed gas. Enclose all $H_2$ lines inside cave in helium jacketing.<br>Design and fabricate H2 gas handling system to approved Design and QA Plan.<br>Weld all joints and use high reliability components on all $H_2$ lines where He jacketing is impractical. Protect all piping and components from mechanical damage.<br>Operate H2 gas handling system to approved Plan.<br>Use thorough leak check procedures during fabrication and before each run.<br>Have cleanup components and procedures to remove contaminants from $H_2$ input gas before cool-down.<br>Helium purge on discharge side of all relief devices. | **IV** | **H-E**<br>**E-B** | EW – 4<br>E -- 2 | EW – 4<br>E -- 3 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| 2 | Vacuum jacket<br>All | Air leak – large or small (due to any cause, but probably to leakage of vacuum piping outside the He jacket or to operator error). | High heat load on $LH_2$ flask if large air leak.<br>Low heat load on LH2 flask if small air leak.<br>Air freezes onto LH2 flask.<br>Possible air/H2 mixture in vacuum vessel if flask ruptures | **III** | **H-E, E-C** if $LH_2$ system does not rupture. See Items A.2, A.3.<br>**H-A, E-A** if $H_2$/air mixture in vacuum space explodes. | See Items Section A and Items C.1, E.<br>Design to ASME code.<br>Surround vacuum jacket and piping with helium jacketing so that vacuum space will be filled with helium, not air.<br>For piping outside cave that is difficult to enclose in helium jacket, build from very strong, reliable components. Provide mechanical guards to protect from damage. Fabricate and check per approved QA Plan.<br>Operate per approved Plan. | **IV** | **H-E**<br>**E-D** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |
| 3 | Vacuum jacket<br>All | Helium leak – large or small | See items on vacuum jacket failure, A.4, A.5<br>Large leak -- He floods insulating space; high heat load on $LH_2$ flask. H2 pressure rises quickly.<br>Small leak -- He invades insulating space; | **III** | **H-E, E-C** | See items on LH2 flask, LH2 piping, vacuum jacket, vacuum piping design and construction, Section A. | **V** | **H-E**<br>**E-C** | EW – 4<br>E -- 3 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| | | | moderate heat load on $LH_2$ flask. Leak easily detectable by vacuum instrumentation. | | | | | | | |
| 4 | $H_2$ gas handling system<br>All | Air leaks – small or large | Air/$H_2$ mixture inside $H_2$ system.<br>Plugs in piping to cold regions. See item C.1<br>Result for small and large leaks is same, except that everything happens faster for large leaks and there is greater potential for combustible $H_2/O_2$ mixtures. | **III** | **H-E, E-C** IF no vacuum vessel or relief failures and redundant relief line is open.<br>**H-B, E-B** if combustible mixture explodes. | See item A.2, A.3, C.1<br>Use redundant vent paths.<br>Design H2 Gas Handling system for high reliability and leak-tightness. Build and test to approved QA Plan.<br>For piping outside cave that is difficult to enclose in helium jacketing, build from very strong, reliable components.<br>Provide mechanical guards to protect from damage.<br>Helium purge on discharge side of all relief devices.<br>Operate entire H2 target system per approved procedures, including QA aspects. | **V** | **H-B**<br>**E-B** | EW – 2<br>E -- 2 | EW – 4<br>E -- 4 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| **D** | FIRES, NATURAL EVENTS | | | | | | | | | |
| 1 | ER2<br>General area of target system | Fire | Increased fire severity if $H_2$ gas is released | **V** | **H-C**<br>**E-B** | Good housekeeping.<br>Local fire extinguishers<br>Initiate $LH_2$ "fast empty" system via introduction of Argon gas into main vacuum. | **V** | **H-E**<br>**E-D** | EW – 4<br>E -- 4 | EW – 4<br>E -- 4 |
| 2 | $H_2$ vent line | Fire at exit of vent line | Possible combustion into vent pipe if air/$H_2$ mixture exists.<br>Possible ignition of materials near vent exit. | **III** | **H-C**<br>**E-B** | Put vent line check valve close to exit to minimize length/volume of air/H2 mixture.<br>Purge line between relief valves and check valve with helium.<br>Locate vent stack in safe area. | **V** | **H-E**<br>**E-D** | EW – 3<br>E -- 2 | EW – 4<br>E -- 4 |
| 3 | Electrical power<br>All | Interruption | Possible unintended valve operation.<br>Loss of refrigeration.<br>Loss of system status indication.<br>Loss of cave ventilation | **I** | **H-D**<br>**E-C** | Use Power-To-Open valves where appropriate.<br>Use Power-To-Close valves where appropriate.<br>Use mechanical gages as appropriate.<br>All personnel out of cave during power outage. | **I** | **H-E**<br>**E-D** | EW – 2<br>E -- 1 | EW – 4<br>E -- 2 |

| # | System -and- Component | Accident -or- Failure | Result | Uncontrolled | | Controls | Controlled | | Qualitative Risk | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Likelihood Bin | Consequence Bin | | Likelihood Bin | Consequence Bin | Uncontrolled | Controlled |
| **E** | OPERATIONAL ERRORS and CONTROL SYSTEM FAILURES | | | | | | | | | |
| 1 | VACUUM<br>Valve | Operator opens with vacuum pump not running and $H_2$ system cold. | Large flood of air into vacuum space, large heat load on $LH_2$ system. Potential H2/air mixture if LH2 flask ruptures. See A.4, etc. | **II** | **H-D**<br>**E-B** | See Section A.<br>Interlock valve(s) to vacuum or pump operation. Mechanically lock valves as appropriate.<br>Operate System per approved procedures. | **IV** | **H-E**<br>**E-D** | EW – 3<br>E -- 1 | EW – 4<br>E -- 4 |
| 2 | CON-TROLS for all Systems | All | Scenarios, results, and failure control/mitigation schemes to be reviewed and documented as part of the design process for the Control Systems. | | | | | | | |

## TABLE 2 –FAILURES CONSIDERED

| # | System -and- Component | Accident -or- Failure | Result |
|---|---|---|---|
| **A** | **COMPONENT RUPTURES** | | |
| 1 a | LH2<br>Target flask or piping inside vacuum vessel | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel, piping, pumping system components, and flask. Assume vacuum vessel, piping, or pumping system components *do not* rupture.<br>Note: H2 release to air if vacuum vessel or system components rupture. See Item A.1b. |
| 1 b | LH2<br>Target flask or piping inside vacuum vessel | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel and flask. Assume vacuum vessel *ruptures*. |
| 1 c | LH2<br>Target flask or piping inside vacuum vessel | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel and flask. Assume vacuum vessel *ruptures*, and helium jacketing *ruptures*. H2 released to exp't. cave.<br>End of exp't. |
| 2 a | LH2<br>Target flask or piping inside vacuum vessel | Rupture due to overpressure (inadequate relief capacity) | $LH_2$ released to vacuum vessel. Rapid pressure rise in vacuum vessel. Assume vacuum vessel does not rupture. |
| 2 b | LH2<br>Target flask or piping inside vacuum vessel | Rupture due to overpressure (inadequate relief capacity) | LH2 release to vacuum vessel. Rapid pressure rise in vacuum vessel and flask. Assume vacuum vessel ruptures, but helium jacketing does not rupture. |
| 3 a | LH2<br>Target flask or piping *outside* vacuum vessel but *inside* cave | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | LH2 release to experiment cave<br>End of experiment. |
| 3 b | LH2<br>Target flask or piping *outside* vacuum vessel but | Rupture due to overpressure (inadequate relief capacity) | LH2 release to experiment cave<br>End of experiment. |

| # | System -and- Component | Accident -or- Failure | Result |
|---|---|---|---|
| | *inside* cave | | |
| 4 a | Vacuum jacket<br>Main vacuum vessel, vacuum pumping system, and all vacuum piping | Rupture -- due to material failure, weld or fabrication failure, or design failure. | Assuming that He Jacketing is not present, air floods vacuum space giving high heat load on $LH_2$ flask.<br>Assume LH2 flask *does not* rupture. |
| 4 b | Vacuum jacket<br>Main vacuum vessel, vacuum pumping system, and all vacuum piping | Rupture -- due to material failure, weld or fabrication failure, or design failure. | Air, assuming that He Jacketing is not present, floods vacuum space; high heat load on $LH_2$ flask.<br>Assume LH2 flask *ruptures*.<br>If $H_2$ vessel ruptures, have air/$H_2$ mixture in vacuum space; see Contaminants Section<br>Possible H2 release to cave. |
| 5 | Vacuum jacket<br>Main vacuum vessel, vacuum piping | Rupture – due to external pressure (from helium jacketing) | He floods insulating space; high heat load on $LH_2$ flask. |
| 6 | Vacuum jacket<br>Main vacuum vessel and piping | Rupture – due to internal pressure (e.g., when $LH_2$ flask ruptures) | $LH_2$ release to helium jacketing.<br>Rapid pressure rise in helium jacketing. Assume helium jacketing does not rupture. |
| 7 | LH2<br>Helium jacketing and associated piping | Rupture -- due to material failure, weld or fabrication failure, or design failure (e.g., over-stress) | Helium release to cave. |
| 8 | LH2<br>Helium jacket and associated piping | Rupture due to overpressure (inadequate relief capacity) | Helium release to cave. |

| # | System -and- Component | Accident -or- Failure | Result |
|---|---|---|---|
| **B** | **COMPONENT FAILURES** | | |
| 1 | REFRIGERATOR<br>Any | Cooling failure (either device or power failure) | $H_2$ pressure rises slowly. Heat load on LH2 is much lower than maximum credible failure. Relief valves open. No safety problems, only operational problems. |
| 2 | REFRIGERATOR<br>Temperature controller | Fails low | $LH_2$ freezes. Possible line plugging with frozen hydrogen.<br>Possible reduction of $H_2$ gas pressure below atmospheric, with increased risk of drawing in air/contaminants. |
| 3 | REFRIGERATOR<br>Temperature controller | Fails high | Inadequate cooling. If refrigerator is ON, gives extra heat load on $LH_2$ system.<br>If refrigerator is OFF, could cause very hot local spot in piping, possibly weakening piping, damaging heater, or causing electrical short to ground. |
| 4 | $LH_2$ flask<br>Relief valve(s) | Fails to open or opens only partially | High pressure in $LH_2$ flask. Possible rupture.<br>$LH_2$ release to vacuum jacket Rapid pressure rise in vacuum jacket, with possible overpressure rupture |
| 5 | Vacuum jacket<br>Relief valve(s) | Fails to open or opens only partially | High pressure in vacuum jacket. Possible rupture.<br>$H_2$ release to helium jacketing (if vacuum jacket ruptures) or to air (if vacuum piping or pumping system rupture), if gas source is $LH_2$ flask failure. Rapid pressure rise in helium jacketing, with possible overpressure rupture |
| 6 | Helium jacketing<br>Relief valve(s) | Fails to open or opens only partially | High pressure in helium jacketing. Possible rupture. Possible damage to or collapse of vacuum jacket if source of gas is He supply failure.<br>$H_2$ release to cave air if He jacketing ruptures and gas source is $LH_2$ flask failure.<br><br>He released to cave air if source is He supply gas failure. |
| 7 | Vacuum jacket<br>Vessel or piping | Damage/rupture from shrapnel created by rupture of the $LH_2$ flask | See items on rupture of vacuum jacket from other causes.<br>$LH_2$ released to cave IF helium jacketing also ruptures |
| 8 | Helium jacketing<br>Vessel or piping | Damage/rupture from shrapnel created by rupture of the vessel inside | $LH_2$ release to cave<br>See Items on rupture of vacuum jacket from other causes. |
| 9 | $H_2$ gas handling system | Broken or leaking | $H_2$ release into ER2 |

| # | System -and- Component | Accident -or- Failure | Result |
|---|---|---|---|
| | Pipes outside cave | | Air/H2 mixture inside H2 gas system. |
| **C** | CONTAMINANTS | | |
| 1 | $LH_2$<br>Target flask or piping inside the vacuum jacket. | Plugged vent line -- due to freezing of contaminants in H2. | Rupture – due to overpressure<br>$LH_2$ release to vacuum vessel.<br>Rapid pressure rise in vacuum vessel |
| 2 | Vacuum jacket<br>All | Air leak – large or small (due to any cause, but probably to leakage of vacuum piping outside the He jacket or to operator error). | High heat load on $LH_2$ flask if large air leak.<br>Low heat load on LH2 flask if small air leak.<br>Air freezes onto LH2 flask.<br>Possible air/H2 mixture in vacuum vessel if flask ruptures |
| 3 | Vacuum jacket<br>All | Helium leak – large or small | See items on vacuum jacket failure, A.4, A.5<br>Large leak -- He floods insulating space; high heat load on $LH_2$ flask. H2 pressure rises quickly.<br>Small leak -- He invades insulating space; moderate heat load on $LH_2$ flask. Leak easily detectable by vacuum instrumentation. |
| 4 | $H_2$ gas handling system<br>All | Air leaks – small or large | Air/$H_2$ mixture inside $H_2$ system.<br>Plugs in piping to cold regions. See item C.1<br>Result for small and large leaks is same, except that everything happens faster for large leaks and there is greater potential for combustible $H_2/O_2$ mixtures. |
| **D** | FIRES, NATURAL EVENTS | | |
| 1 | ER2<br>General area of target system | Fire | Increased fire severity if $H_2$ gas is released |
| 2 | $H_2$ vent line | Fire at exit of vent line | Possible combustion into vent pipe if air/$H_2$ mixture exists.<br>Possible ignition of materials near vent exit. |
| 3 | Electrical power<br>All | Interruption | Possible unintended valve operation.<br>Loss of refrigeration.<br>Loss of system status indication.<br>Loss of cave ventilation |

| # | System -and- Component | Accident -or- Failure | Result |
|---|---|---|---|
| **E** | OPERATIONAL ERRORS and CONTROL SYSTEM FAILURES | | |
| 1 | VACUUM<br>Valve | Operator opens with vacuum pump not running and $H_2$ system cold. | Large flood of air into vacuum space, large heat load on $LH_2$ system. Potential H2/air mixture if LH2 flask ruptures. See A.4, etc. |
| 2 | CONTROLS for all Systems | All | Scenarios, results, and failure control/mitigation schemes to be reviewed and documented as part of the design process for the Control Systems. |