Title
Response to Absorber-Focus Coil Preliminary Safety Review Panel

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Response

To

Absorber-Focus Coil Preliminary Safety Review Panel

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In this document we provide responses to the various issues raised in the report of the Preliminary Safety Review Panel (see http://mice.iit.edu/mnp/MICE0069.pdf). In some cases we have made design changes in response to the Panel's suggestions. In other cases, we have chosen not to do so. In a few cases, we indicate our plans, although the tasks have not yet been completed. For simplicity, the responses are organized along the same lines as those of the Panel Report.

We are very grateful to the Panel for the in-depth study that they carried out of our proposed hydrogen safety system.[1] We benefited enormously from the review and the subsequent report outlining the issues listed below.

Hydrogen Gas Handling and Venting System

Issue: *Whether the evacuated buffer tank is needed or if it is better just to vent the hydrogen directly outside.*

Response: We have decided that the simpler approach suggested by the Panel has merit and have adopted it. See Appendices 1 & 2.

Issue: *The possibility of having just redundant burst disks on the vacuum relief line instead of a burst disk plus a relief valve.*

Response: The advantage of having a relief valve as well as a burst disk is that the relief valve will close again after activation, preventing backstreaming into cold spaces. For this reason, we still plan to use relief valves. See Appendix 2 for details.

Issue: *The option of having completely separate vent systems for the absorber and vacuum spaces.*

Response: We have concluded that it is a good idea to have separate vent lines for the absorber and vacuum space. In particular, if a bilge space at the base of the absorber is implemented, then the hydrogen release in the event of a catastrophic event will be more controlled. See Appendix 2.

Issue: *The detailed specification of relief valves and hydrogen detectors and whether hydrogen detectors are appropriate in the vacuum line.*

Response: Work is in progress to develop detailed specifications for the relief valve. The issue of how effective the hydrogen detectors are, and where they are placed, needs further study; we are aware of the problem. Work is in progress to address this issue.

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[1] See http://hep04.phys.iit.edu/cooldemo/afcswg/review/designpaper.pdf .

Issue: *We believe that hydrogen detectors are needed in the ventilation system and in the personnel space around the experiment.*

Response: We are aware of, and concur with, this need. Hydrogen detectors will be placed in the ventilation system and around the equipment. Refer to Appendix 2 for a diagram indicating hydrogen detector placement.

Issue: *The level to which piping should be argon jacketed should be examined.*

Response: The extent to which we argon jacket the equipment and piping is still being looked at. The criterion proposed by the Panel is that the pressure in the hydrogen system remain above atmospheric pressure to prevent the ingress of air. In places where this is not possible, argon jacketing will be used to prevent air from entering the system. The main issue we have with the system is in the management of the liquid hydrogen. If the pressure in the absorber rises, then we need a relief valve to operate, either to let the hydrogen back into the storage system or to vent it outside. If we wish to let the hydrogen back into the storage system, then we need a pressure differential across the relief valve close to PV3 (see Fig. 2 in Appendix 2), which, in turn, means that the pressure in the hydride bed must be less than the operating pressure in the absorber. That is, to take up any excess hydrogen without venting it will be necessary to operate the hydride bed cold and at low pressure. The system, as configured at the moment, has a relief valve back to the hydride bed that acts when the absorber is at the upper end of its allowed temperature range (20 K). (If the temperature rises above 20 K, the hydrogen will be vented to atmosphere when the pressure reaches 1.6 bar, the design pressure of the windows.) We intend to enclose the hydride bed and associated piping in an argon jacket to eliminate the possibility of air ingress. Even if we abandon the desire to recover the hydrogen during temperature excursions, and simply permit it to vent outside, we probably cannot avoid the need to operate the hydride bed at sub-atmospheric pressure during the condensation phase. In our view, an approach that would always keep the hydride bed above atmospheric pressure has drawbacks, mainly in terms of difficulty with liquid-level control. We are in the process of examining our philosophy on this rather complicated matter.

Issue: *The possible replacement of the flame arrestor with a vent pipe with an inert atmosphere should be considered.*

Response: This change has been implemented in our design.

Issue: *The possibility of adopting the Fermilab requirement concerning the vacuum system volume relative to the liquid volume should be examined.*

Response: We have considered adopting the Fermilab 52:1 volume ratio requirement and concluded that we can satisfy the RAL safety requirements without such a large buffer volume. Finite-element calculations were employed to demonstrate that the pressure increase due to rupture of the absorber window is manageable. See additional comments in Appendix 2.

Research and Development of the Metal Hydride System

Issue: *The use of the hydride storage system is innovative and has a number of advantages. It has been recognized that this system requires more active control. Specifying and testing the hardware perhaps even at a small scale would be very valuable. Reliable operation of this system and its controls will be critical to successful operation of the absorber. Safety issues associated with the hydride system including relief valves, pressure vessel ratings and the impact of utility failures will need to be examined. Particular care should be taken to ensure that the hydrogen gas system through the experiment never drops below atmospheric pressure. We feel that R&D time spent on this system in advance will pay off in a more reliable system.*

Response: We have developed a plan for testing the hydride system. The plan involves building the hydrogen system for the first MICE absorber cell. As part of this process, we are looking at how the system will be controlled. This has led to some minor changes in the instrumentation. We have received additional information from the supplier regarding the behavior of the hydride in the beds. An R&D plan has been submitted for inclusion in the development program for the coming UK financial year. See Appendix 3. As discussed earlier, it may not be desirable to operate the hydrogen bed above atmospheric pressure at all times, so an argon jacket may be required.

Window Development

Issue: *The current R&D activity on the development of welded seals for the windows should continue. In particular, the welding of a flange containing the final thin window design should be done. In addition, development and reliability testing of the indium seals should continue. This should include repeated thermal cycling. If the double indium seal design is chosen, monitoring of the space between the indium seals should be done but decisions need to be made on what you are monitoring for and what actions or interlocks are triggered upon finding pressure in that space.*

Response: The R&D plan for the welded-window option already addresses this point. Thermocouples will be attached at the window-to-flange junction and at various points around the window to see what temperatures are reached in each location during welding. While the bolted window remains our baseline choice, final selection of this option is conditional upon the satisfactory demonstration of a reliable seal with repeatable performance. While it is possible to monitor the space between a double indium seal for leaks, it is not clear that this is the best scheme to employ. Insofar as the monitoring pipes connected to the seal gap area are non-trivial to connect, and could themselves represent a leak risk, it is not obvious that this approach enhances system safety and reliability. The only place the hydrogen can leak to is the absorber vacuum space, and this is more easily monitored for hydrogen than is the inter-seal gap. If there were a significant leakage of hydrogen into the absorber vacuum space, the heat leak into the absorber would increase markedly. A pressure of about 10^{-2} torr would correspond to a heat leak of roughly 5 W into an absorber; more than this would be unacceptable. Our upper leak rate limit of 10^{-2} torr L s^{-1}, ensures that we can maintain a pressure below 10^{-4} torr in the absorber vacuum space with a 100 L/s pump—well below the problem regime. Actions to be taken as a result of monitoring the absorber vacuum space pressure are summarized in Table 1.

Table 1. Actions taken based on monitoring of absorber indium seal leak rate.

Absorber vacuum pressure	Action taken
Above 1×10^{-2} torr	Stop He cooling and commence warm-up of the absorber
Below 1×10^{-2} torr	Continue monitoring and repair the seal at the next opportunity to warm up

Other Recommendations

Recommendation 1: *The requirement for "intrinsically safe" electrical equipment for use in the experiment may not be always possible. Other techniques such as turning off electrical power in the event of hydrogen gas detection should be considered but the consequences of doing so should be taken into account so that additional hazards are not created. A careful review of all possible ignition sources even those removed from the hydrogen area should be done. A detailed hazardous analysis on this topic should be prepared.*

Response: Most of the standard cryogenic probes are well within the "intrinsically safe" power limits set by the NEC. In addition, pressure valves and other equipment can be made "intrinsically safe" by straightforward modifications (usually, a sealed cover or container). We have to carefully consider what the thresholds are for some minor action (e.g., increase or decrease the metal hydride bed temperature) as opposed to major action (e.g., system purge or power shutoff).

Recommendation 2: *There is a significant hazard with stray magnetic fields causing tools and other equipment to become projectiles. Restricting access to the experimental area and attention to house keeping should reduce this hazard.*

Response: Access into the experimental hall will be restricted, and the area around the experimental hall will be fenced. Before switching on the magnet power supplies, the MICE Operating Procedures will require that a person on shift inspect the fenced area and remove any tools or other objects that might become projectiles.

Recommendation 3: *Under no circumstances should equipment be operated with the thin absorber or vacuum windows exposed.*

Response: We agree that this is a critical requirement and it will be one of the MICE Operating Procedures.

Recommendation 4: *The construction of the hydrogen gas system should use welded pipes, metal seals and other flanged connections. Compression fittings, and plastic tubing should not be used. Careful helium leak testing of the system should be done before operation. This leak testing should be part of the formal system certifications.*

Response: This has always been our design philosophy. All hydrogen gas system pipes are welded, and all required joints will be made with Conflat or other suitably robust flanged connections. Table 2 below summarizes pipe joint details. No Swagelock fittings or plastic tubing will be employed in the hydrogen piping system.

Table 2. LH_2 absorber joints and welding.

	Indium-Seal[a] ϕ 1 mm	Welding Al–Al	Transition Al–SS	Welding SS–SS	VCR[b] Ni
Window					
Body		Y			
Body-Window	Y (Double)				
H2 Pipe		Y	Y	Y	Y(3/4")
Cold-He In		Y	Y	Y	Y(1/2")
Cold-He Out		Y	Y	Y	Y(1/2")

[a] Backup option is Helicoflex seal.

[b] Backup option is KF flange plus Helicoflex seal.

Recommendation 5: *Hydrogen gas detectors should be installed in the personnel areas around the experiment. Decisions should be made as to what actions should be taken if hydrogen is detected. For example, evacuation alarms, turning on of ventilation systems or notification to the fire department may be appropriate.*

Response: Hydrogen detectors will be installed at various locations in the experimental hall. If hydrogen is detected, these sensors will trigger the personnel evacuation alarm and initiate a high-rate mode of the ventilation system.

Recommendation 6: *In general, interlocks, alarms and controls should be carefully thought out and specified. Response to alarm states should be carefully considered so as not to increase the hazard or unnecessarily impact operations. Critical control systems should be placed on uninterruptible power supplies. Controls associated with safety interlocks should be put on safety-rated programmable logic controllers. Other controls associated with hydrogen system operations should be placed on separate appropriately robust devices (i.e. programmable logic controllers).*

Response: We agree with this recommendation, and our design of the MICE safety system will take it fully into account.

Recommendation 7: *The good work started with the HAZOP process should be continued and expanded. This should include a scenario in which both the absorber and vacuum windows fail at the same time.*

Response: This remains our intention. We understand that the HAZOP presented at the review was only preliminary. As the operating modes become more fully defined, we will proceed to the next stage of HAZOP analysis. Our definition of a "safe" design is one that will tolerate two simultaneous failures, so the scenario with two windows failing is already part of our analysis. We will also do a Failure Mode and Effect analysis for all identified failure modes.

Recommendation 8: *The collaboration should plan in advance how it will respond to leaks or problems of various levels with the absorber system. Making these decisions in advance will help prevent the temptation to continue running with a problem.*

Response: This is very good advice and we will follow it. Various scenarios of absorber leaks and equipment malfunctions will be analyzed and the appropriate response procedures will be specified in the written MICE Operating Procedures.

Recommendation 9: *The potential of liquid hydrogen being pushed into a warm part of the piping with resulting flashing should be considered carefully. Techniques such as heat sinking the pipes or using vertical runs should be examined. This problem could have a significant impact on system operations.*

Response: This is being addressed together with our design approach to the LH_2 Level Control. See Appendix 4 for further comments.

Recommendation 10: *A failure mode analysis should be done on the possibility of leaks between the helium and hydrogen portions of the heat exchanger. As an example, the helium circuit operates at 18 bar, much higher than the absorber pressure. Thorough testing of the heat exchanger is needed.*

Response: The helium system will be designed for 18 bar, and leak tested to a high standard, at 1.25 times the design pressure, after the necessary thermal cycling, as specified in our leak test requirement, Table 4-4 of the Preliminary Design Document (reproduced below for completeness). This should minimize the possibility of such an event. Nevertheless, as part of the HAZOP process we plan to assess how this problem might manifest itself in operation, how to detect it, and how to deal with it.

Table 4-4. Vacuum leak checking specifications.

Location	Max. acceptable leak rate[a) (mbar L s^{-1})
Absorber body	10^{-9}
Absorber heat exchanger	10^{-9}
Focus coil He tubes	10^{-9}
Focus coil cryostat	10^{-7}
RF cavities	10^{-8}
Absorber safety vacuum	10^{-7}

a)Measured at 300 K.

Recommendation 11: *Quality control standards for the window thickness should be developed. The current testing and QC standards are quite impressive for this early stage of the project.*

Response: A draft Quality Control and Quality Assurance document has been prepared and will be implemented once approved by the MICE Project Manager. Three levels of control are identified to ensure proper attention to QA/QC issues:

- **Level 1:** systems, components, structures, and materials that are unique or whose failure could jeopardize facility personnel safety, safe emergency shutdown capability, or ISIS operation
- **Level 2:** systems, components, structures, and materials whose failure would render MICE inoperable for substantial periods, damage other critical equipment, decrease MICE performance, or delay start-up
- **Level 3:** all other items

Recommendation 12: *The list of certifications required should be reviewed to ensure that all the certifications required can in fact be met. If it is not possible to meet a given certification, the impact of not meeting the certification on system safety should be considered and explained to the RAL external safety committee.*

Response: We will do this as part of the process of getting ready for the RAL "external" safety review.

Appendix 1. Buffer Volumes

Our original design, reproduced here in Fig. 1, utilized a common buffer volume for venting both the absorber and its surrounding vacuum space. In both cases, the buffer volume was separated from the working regions by means of relief valves and burst disks. The Panel has convinced us that it is more effective to vent directly to the outside, and we now intend to do so. The RAL safety code does not demand a buffer volume of 52 times the liquid-hydrogen volume, and our finite-element calculations have convinced us that a spill does not develop unsafe pressures in the system. For these reasons, we are satisfied that the current buffer vacuum space, roughly 12 times the liquid-hydrogen volume, provides adequate safety margin.

The new design (see Appendix 2) does include a 1 m^3 buffer volume on the input line to the absorber. This simplifies level control and provides some window protection by providing an overflow space.

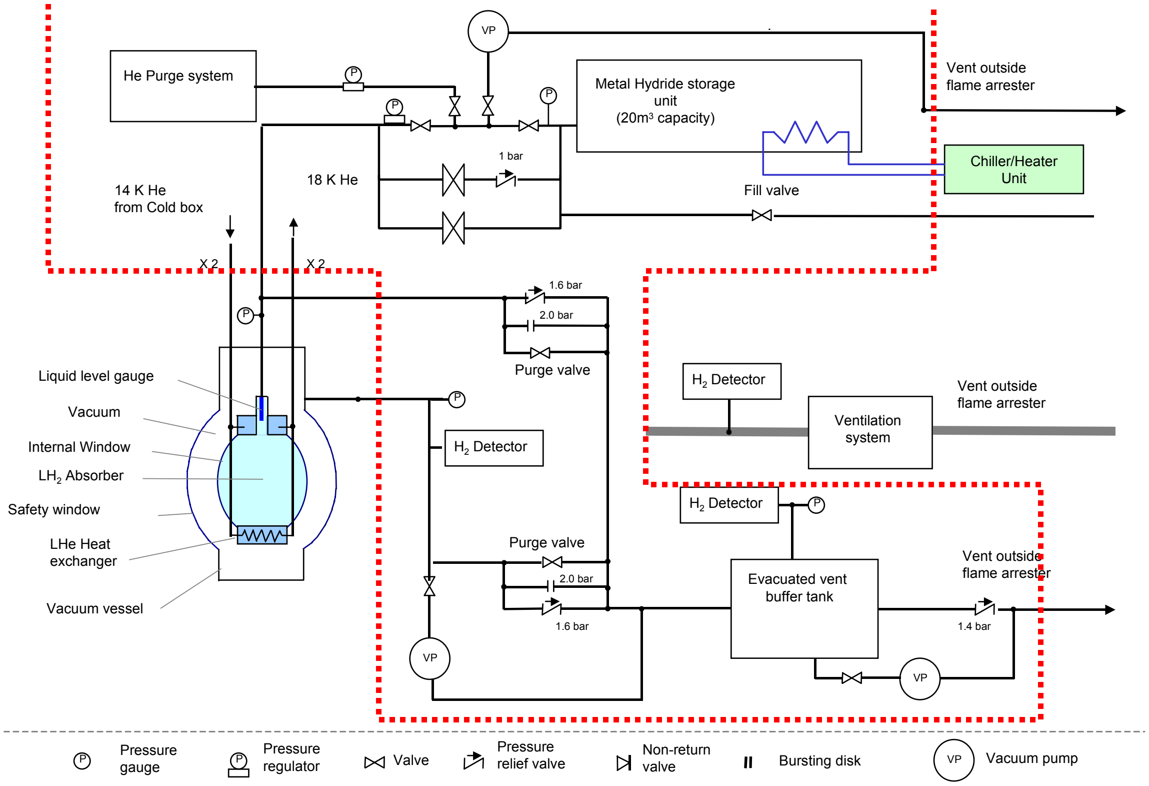

Figure 1. Original design of hydrogen system presented at Preliminary Safety Review.

Appendix 2. Changes in MICE Hydrogen System

The updated diagram of the MICE hydrogen system is shown in Fig. 2. As noted earlier, we have adopted suggestions from the Review Panel in the following areas:

- the original buffer vessel on the relief line has been removed
- a venting manifold filled with nitrogen has been added
- separate vent lines for the absorber and the absorber vacuum space have been implemented

In addition, we have added a 1 m^3 buffer vessel on the input line between the hydride bed and the absorber. After studying the layout more carefully, we have decided to eliminate the ventilation system in favor of placing most of the hydrogen equipment within the hydrogen extraction hood.

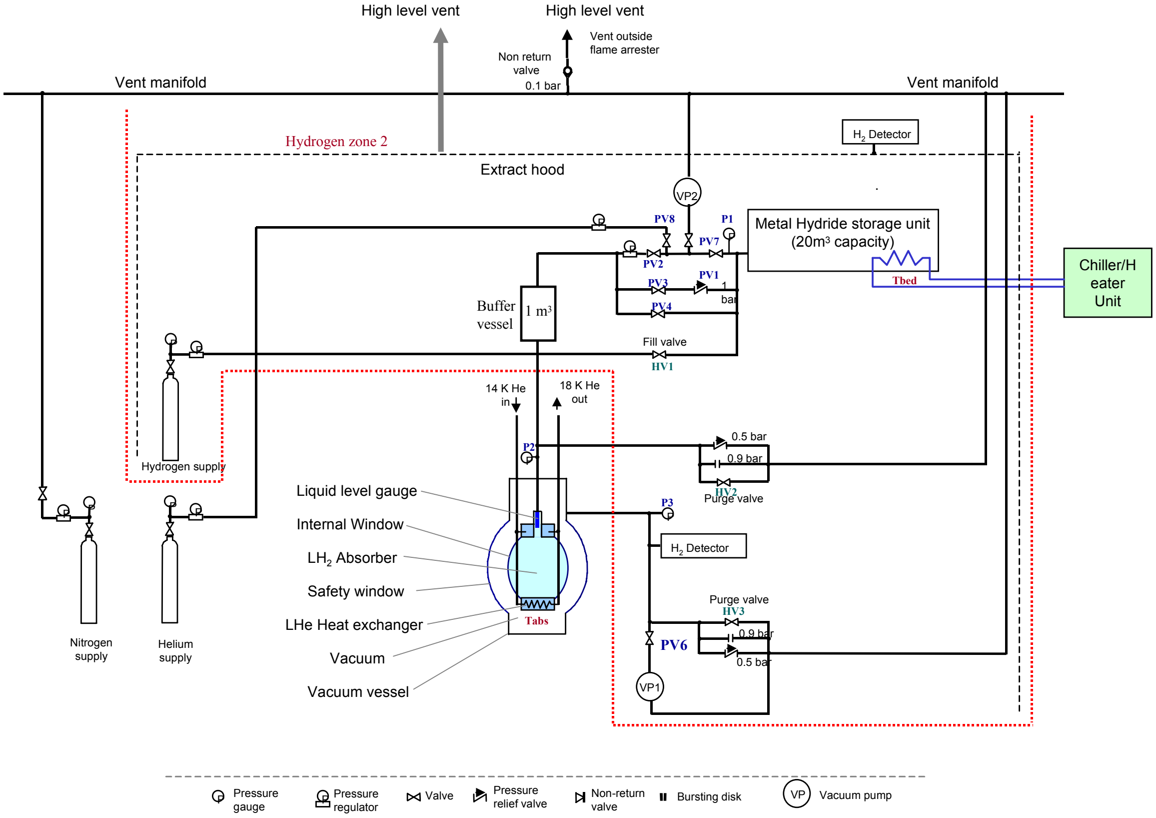

Figure 2. Revised baseline design for hydrogen system.

Appendix 3. R&D Program on Metal Hydride Storage System

In considering what R&D should be done, the first issue to decide is whether we should study a small-scale version of the final system or a full-scale prototype. We have chosen to study a full-scale system, with the idea that it will later be used as the first unit for MICE. Due to funding limitations, the R&D program has not yet been initiated, but we hope for funding approval in 2004–2005.

The R&D goals of the program are listed below:

- establish working parameters for a hydride bed in the three operational modes, storage, filling the absorber, and emptying the absorber
- measure absorption and desorption rates as a function of relevant parameters, such as temperature and pressure
- determine the purity of the hydrogen and the effects of impurities on system operation
- determine power requirements for hydride bed heating and cooling
- define the instrumentation (safety relief valves, sensors, and interlocks) required for safe and reliable operation of the system

The program outlined is an ambitious one, but is clearly necessary in order to be assured of a safe and robust system for MICE.

Appendix 4. Hydrogen Level Control

The matter of LH_2 level control is a complicated one. The first issue is to decide which of the possible variations we need to respond to. For example, the hydrogen level will vary significantly due to temperature changes in the absorber. Density variations of the liquid could result in 1–2 L changes in volume. It is obvious that such large changes cannot be accommodated in small pipes, since a 25-mm diameter pipe with 1 L volume is 2.2 m in length. Fortunately, such level changes will be relatively slow under normal operating conditions. It takes about 50 kJ to raise the temperature of 20 L of liquid hydrogen from 14 K to 18 K. Since the nominal heat load into the absorber is only a few watts, the time to go from 14 K to 18 K is roughly 5–10 hours. We expect that the most significant effect of hydrogen level changes would be intermittent gas boil-off, especially in a horizontal pipe.

We have considered possible locations where the liquid-hydrogen level could be monitored and controlled. The absorber neck tube has insufficient volume to accommodate level changes, and the adjacent horizontal pipe would clearly be impractical. The exit vertical pipe is likewise impractical, as it would only work if the horizontal pipe is in thermal equilibrium with the liquid, and it has too little volume. Our present concept is to employ a 1 m^3 external buffer volume, as shown in Fig. 2. Even assuming no return to the hydride bed, this buffer could accommodate a volume change of 0.5–1 L before making it necessary to activate the relief system.