NASA Suggested Requirements to Chilean Government For Miner Rescue System Design

September 10, 2010

Executive Summary

On a site visit, to the San Jose Mine near Copiapo, Chile during the week of 30 August 2010, discussions were held between NASA and Chilean Government officials about the design of the vehicle that will ultimately be needed to lift the trapped miners to safety. It was offered that NASA assistance might help refine and define some of the requirements for this vehicle. After the NASA officials returned to the United States, this offer was accepted by the Chileans. Beginning 7 September, NASA engineers, primarily from the NASA Engineering and Safety Center (NESC), and NASA medical personnel worked on producing this document. While NASA does not have significant expertise in mining related matters, NASA does have extensive experience in defining requirements, designing unique vehicles, and caring for individuals who are exposed to harsh environments. The experiences NASA can offer, therefore, allow comment on the design considerations that may be of use to Chilean officials who will shortly be required to make selection decisions on this vehicle.

This document outlines the miner rescue operations concept as NASA currently understands it and provides guidance and recommendations for components that should be included in the miner rescue system to ensure the safety and health of the miners as they ascend from the mine floor to the surface. The document also discusses design features of the rescue system that will help avoid the introduction of harmful medical conditions that could result from the extraction process. Additionally, a supporting rationale for each suggestion gives the reasoning behind the recommendation.

The overall miner rescue system includes several components, including the Escape Vehicle (EV), hoist system, communications devices, and miner protective equipment. NASA's suggested requirements are divided into two areas since many of the components of the overall rescue system could be self-contained and separate from the EV. Suggested requirements for the EV hardware, which is viewed as a long-lead item, are provided first. Suggested requirements for the other components in the overall miner rescue system are viewed as evolutionary in nature and may not be incorporated directly in the EV design, but attached to the occupant or the vehicle after it has been designed and manufactured.

Because of the complexity of mining operations, the dynamic nature of the situation at the mine, and possible changes to the key assumptions of the rescue, these suggested requirements in this document are not intended to provide a complete specification of the EV. Therefore, the technical content of these requirements should be considered as design guidelines, best practices, and the basis for asking intelligent questions of the actual Chilean EV designers.

This document was written with the assistance of two Spanish-speaking NASA engineers. An attempt was made to make this document understandable to Chilean individuals who speak English but whose primary language is Spanish. In many cases, however, precise English explanations may be required to ensure that the recommendations are not misinterpreted. In those instances where Chilean officials desire clarifications, NASA personnel are ready to assist in ensuring an accurate understanding of the technical content of this document and intent of the suggested recommendations.

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1 Background

The suggested requirements in this document were developed to help Chilean government officials select the miner EV design. These suggested requirements are based on information available to the NASA team as of September 9, 2010. Since the situation at the mine is very dynamic, NASA personnel may not be aware of current conditions or additional requirements decided upon by Chilean officials. Therefore, the suggested requirements in this document are not intended to provide a complete specification of the EV. The technical content of these requirements should be considered as design guidelines, best practices, and the basis for asking intelligent questions of the actual Chilean EV designers.

1.1 Organization of the NASA Suggested Requirements

Because the construction of the EV is expected to take the longest amount of time, the NASA team has focused on providing the set of primary requirements, listed in Section 2.1, needed to begin manufacturing of the EV as soon as possible. Additional equipment or systems required for the miner extractions, which are not expected to be a part of the EV itself, are termed the Rescue System (RS). RS suggested requirements are listed in Section 2.2. Additional design and operational considerations listed in Section 3 include recommendations that might be considered as solutions to some potential design problems.

1.2 Guiding Principles

A guiding design principle of the NASA team was not to introduce unnecessary complexity to the EV design. The design of the EV should address potential hazards to the miners and the equipment. Major medical hazards/risks include orthostasis, hypoxia, and thermal issues. Major equipment hazards/risks include collateral damage, risk of EV getting stuck in the escape shaft during descent or ascent, and risk of an uncontrolled EV descent.

The EV is one component of the broader RS, which encompasses the EV, its hoisting mechanisms, required components that may be attached to the EV, and devices or components that may be carried onto the EV by the occupant. When this document discusses the EV, it refers to the primary structure of the lift cage or capsule itself. It is recognized that many of the RS components, such as breathing apparatus, ventilation and temperature controls, bodily protection, etc., are evolving and will continue to evolve during the fabrication of the EV. The intent is to provide a set of primary requirements to begin manufacturing of the EV as soon as possible while the designs of the other RS components are being refined.

1.3 Rescue Operations Concept

The design of the escape vehicle must also fit the rescue operations concept. The NASA team's understanding of the operations concept includes the following key points:

- One miner rescued at a time in a pre-determined order.
- Escape vehicle will be tested before deployment and inspected for damage, wear, and tear during use.

- Consumables (oxygen, batteries, water, etc.) will be onboard and replenished at the surface for each trip.
- Miners will hydrate before beginning ascent in the rescue shaft. Note: A suggested fluid loading protocol shall be developed by the NASA team and provided separately to the Chilean medical authorities.

1.4 Design Requirements and Objectives Provided by the Government of Chile

It is the understanding of the NASA team that the following design guidance has already been provided by the Chilean government to the EV designers:

- Maximum EV outside diameter: approximately 58.4 cm (23 inches)
- Maximum EV height: approximately 2.5 m
- Weight limit: Rope can support a maximum of 16,000 kg. Note: the capability of the hoist system was not known.
- The EV must be able to be re-used approximately 40 times (33 miners plus potential test runs).
- The EV must work in a vertical (90 degrees) or tilted shaft, up to the maximum angle being drilled (82 degrees).
- Transmitting antennae will be mounted on the top and bottom of the EV. One of the transmitting antennas will be for a cardiac and respiratory rate monitor to be placed on each miner.
- There will be winches located at both the top and bottom of the escape shaft.
- Face and head protection will be provided to the miners.
- A voice communication system will be provided, and a video camera will be used to visually monitor all miner ascents.
- The EV will provide sufficient compressed air for over an hour: either three small 12-liter diving air tanks or two 18-liter tanks attached to a manifold. Note: NASA Doctors recommend Oxygen in place of compressed air.

2 Design Requirements Submitted by NASA Team for Chilean Consideration

Each recommended design requirement includes explanatory rationale. Since the sole purpose of the system is the safe extraction of the miners, medical requirements are integral to the design process. Medical requirements are listed first in Section 2.1 and Section 2.2. Suggested requirements are *not* listed in any priority order.

2.1 Escape Vehicle (EV) Design Requirements

The suggested requirements listed below are limited to the design of the EV, which is one component of the overall miner rescue system.

2.1.1 EV shall have a lower surface capable of bearing the full weight of the occupant. *(Medical)*
Rationale: Potential medical complications dictate that the occupant be able to stand on the floor and not be fully suspended in the vehicle.

2.1.2 EV or paloma-type device shall have portable oxygen tanks that are protected from debris or damage. The tanks will be of sufficient size (D or E tanks in parallel) to provide medical grade oxygen at a rate of 6 liters per minute for up to 2-4 hours, and used tanks will be changed out for fresh tanks upon extraction. *(Medical)*

Rationale: Having oxygen available will prevent hypoxia and hypercarbia. Provides oxygenation while simultaneously preventing increased CO2 rebreathing. Several of the miners have lung disease.

2.1.3 EV shall accommodate individuals with larger shoulders. *(Medical)*

Rationale: Need to allow occupants with wide shoulders to use the full diameter of the escape shaft if required, beyond the diameter of the EV primary structure.

2.1.4 EV shall include a loose harness system. *(Medical)*

Rationale: A loose harness restrains occupant motion in the event of loss of consciousness or severe anxiety. Note: need to consider potential interaction with a secondary escape system, if used.

2.1.5 EV shall include an adjustable seat or ledge to allow the occupants to shift their weight.

Rationale: Allows occupant to take load off feet and legs, and to bend knees to combat orthostasis.

2.1.6 EV shall provide occupant hand-holds, either separate hand-holds or part of the primary structure.

Rationale: Allows occupant to stabilize position and shift weight during ascent to combat orthostasis.

2.1.7 EV shall allow for a single miner to enter and secure himself and the vehicle for ascent. EV ingress shall also accommodate an incapacitated miner, and should be operable by the last person.

Rationale: Some miners may have injuries or medical issues at the time of rescue. Eventually, only one miner will be left in the mineshaft so there will be no one to help him into the EV and prepare it for ascent.

2.1.8 EV shall include a "pull down" capability at the mine level to complement the "hoist up" capability based at the surface.

Rationale: In the event of the EV jamming in the shaft, the miners should be able to pull down either the entire vehicle or maybe just the miner himself if he can drop out of the cage through a bottom hatch.

2.1.9 Volume requirements for additional equipment (e.g, oxygen, medical monitoring equipment, batteries, cameras, lights, signal transmission equipment, etc.) shall be assessed and a determination made as to whether to incorporate this volume into the primary structure, or include a separate system (like a larger paloma) above the vehicle and connected by umbilical.

Rationale: The EV design is volume constrained and the use of this limited volume needs to be carefully managed. Space for additional necessary equipment needs to be assessed and accounted for in the design. A design utilizing a separate payload carrier provides several benefits including the maximization of the space for human occupant in the primary EV, simplifies manufacturing, and makes it easy for multiple units to be fabricated, which can be easily changed out or replaced between lifts should any components in the paloma-type device become damaged or inoperable.

2.1.10 EV shall be designed with appropriate factors of safety to prevent structural failures. Relevant factors of safety should be obtained from a recognized standards organization.

Rationale: Structural failure can cause injury or death to personnel. In the United States, the designs of equipment used to lift personnel usually comply with standards published by the American Society of Mechanical Engineers, Personnel Lifting Standards, ASME B30.23, which imposes the requirement for a minimum factor of safety of 5.

2.1.11 EV shall be proof tested to demonstrate structural integrity under severe loading conditions. The proof test shall be performed using a load specified by the relevant standard (for example, ASME B30.23 requires 150 percent of the rated load). As a minimum, a "dynamic" proof test should be performed. The test is performed by suspending a loaded vehicle, then lowering it at a speed not less than the maximum speed used during operations. Once the designated speed is reached, the vehicle descent is halted by applying the hoisting equipment brakes and then allowing the vehicle to hang for a period of time. The proof test should also include the application of "pull-down" loads that might be applied by the winch in the mine. After the test, the vehicle shall be inspected by qualified personnel.

Rationale: Appropriate testing should be performed to demonstrate a sufficient design and manufacture. Design or manufacturing errors may cause structural failure that could result in personnel injury or death.

2.1.12 EV shall have a primary structural load path directly from the top hoist point to the bottom hoist point.

Rationale: With a dual upper and lower winch system, the structure should be capable of supporting the differential loading between the upper and lower attach points during an extreme loading event, such as freeing a jammed vehicle.

2.1.13 EV shall be self-aligning at both ends of the escape shaft and during transit.

Rationale: The last miner to be extracted will have no help in manually aligning the vehicle for initial entry in the escape shaft. (for example, potential EV self-alignment methods include rails, funnels, etc).

2.1.14 EV shall be free to slide within the escape shaft. Any exterior surfaces shall be smooth with no sharp edges or protrusions. Sufficient spare parts or surfaces that contact the shaft walls shall be provided to replace worn or broken parts.

Rationale: The escape shaft wall roughness may, depending on design, cause significant wear during operations.

2.1.15 EV lower surface and upper surface shall be of an open grid or perforated construction. The grid density should be sufficient to provide protection from falling rocks and other debris.

Rationale: While providing protection against any debris generated during the transportation process, it should also provide ventilation and occupant visibility above and below the EV.

2.1.16 If a secondary escape system is deemed necessary in the event that the EV becomes stuck, then the top and/or bottom shall have mechanisms to allow opening and egress. The release mechanisms shall be designed to prevent inadvertent or accidental opening. Remote operation from the surface may also be necessary for an incapacitated occupant. A backup system is then required to either lift or lower the occupant back to safety.

Rationale: A method to egress the vehicle once inside the escape shaft is a necessary component for a secondary escape system.

2.1.17 EV shall be tolerant of center of gravity (CG) offset.

Rationale: During ascent, any shifting of the occupant's weight or CG offset bias may misalign the EV within the escape shaft and result in jamming.

2.1.18 EV design shall adequately account for friction between the EV and the escape shaft surface.

Rationale: Friction can introduce excessive wear and tear on the vehicle, and cause the vehicle to become stuck in the escape shaft. Example methods to compensate for friction include spring loaded rollers, Teflon blocks, skids, and dry lubricants.

2.1.19 All EV latching mechanisms shall have fail-safe designs. Latching mechanisms should be able to be opened by the occupant and an external operator.

Rationale: Dual action or fail-safe mechanisms will prevent inadvertent activation. Bumping the latching mechanisms should not activate them.

2.1.20 The power requirements for additional equipment (for example, oxygen, medical monitoring equipment, fans, cameras, lights, signal transmission equipment, etc.) shall be assessed and a determination made regarding integration of the energy source into the EV. If an energy source is integrated with the EV, the energy source shall provide power with sufficient margin (recommend a minimum of 50 percent margin) and be placed and connected in such a manner as to allow quick and easy replacement at the surface between trips.

Rationale: Power needed for critical safety monitoring devices that do not have self-contained battery sources needs to be assessed and provided.

2.1.21 Electrical power supplied to/by the EV shall be low voltage (for example, 12 Volts DC).

Rationale: Safety of occupant. Any components requiring electricity can be powered by low voltage sources.

2.1.22 EV shall be capable of being cleaned between hoists.

Rationale: Vomit, urine, excessive dust, etc., could be harmful to vehicle components and should be removed between hoists, as necessary.

2.1.23 EV shall be configured such that occupant is able to move at least one hand to his face. Rationale: Over the potentially long transit, the occupant must be able to have at least enough range of motion to adjust protective equipment (helmet, mask, and goggles).

2.2 Rescue System (RS) Design Requirements

The following recommended requirements address components of the overall miner RS other than the EV, or they address broader system-level issues.

2.2.1 The occupant shall have a non-rebreather plastic oxygen mask (will be placed on 6 liters per minute O2 flow rate). The mask shall have a reservoir. *(Medical)*

Rationale: An oxygen mask will prevent hypoxia and hypercarbia. Provides oxygenation while simultaneously preventing increased CO2 rebreathing. The mask can be a simple green non-rebreather used in ambulances, and run from an O2 tank. Several of the miners have lung disease.

2.2.2 RS shall include video cameras providing a view up the escape shaft and down the escape shaft as the vehicle is hoisted. *(Medical)*

Rationale: Video cameras give the occupant and EV hoist operators situational awareness for rough areas, as well as when they are close to reaching their destinations. Operators must be able to see up and down the shaft to understand and monitor external conditions as the vehicle is hoisted and in the event it becomes jammed.

2.2.3 RS shall include a non-pneumatic compression garment or other devices to combat orthostasis in the occupant, yet allow some movement of the lower extremities. *(Medical)*

Rationale: Orthostasis is the top health risk to the occupant during the potentially long transit from the mine floor to the earth's surface.

2.2.4 RS shall provide two-way audio communication capability with the EV occupant. *(Medical)*

Rationale: Due to the potentially long transit time, communication with the miner is imperative to monitor and assess his health, provide status and generally maintain the morale of the miner.

2.2.5 RS shall have a camera focused on the EV occupant. *(Medical)*

Rationale: Camera required to monitor miner's health and awareness and potentially allow the miner to communicate in the event of loss of audio signal.

2.2.6 RS shall provide cooling for the EV occupant. *(Medical)*

Rationale: Overheating can lead to occupant stress which could become a medical issue during transit. Electric fans, drinking cool fluids, and using commercially available passive cooling vests may be cooling options.

2.2.7 RS shall provide lighting suitable for video monitoring and occupant vision. *(Medical)*

Rationale: Lighting is required for occupant health monitoring and morale.

2.2.8 RS shall include medical equipment for real-time vital signs monitoring; including heart rate, rhythm (in lead II), and pulse ox. *(Medical)*

Rationale: Due to the potentially long transit time, monitoring miner health is imperative.

2.2.9 RS shall provide tinted eye protection (goggles with UV A and UV B protection) during transit and at surface. *(Medical)*

Rationale: Occupant's eyes could be damaged by debris during transit and by bright sunlight upon exit from the mine. Tinted eye protection prevents UV A and UV B exposure upon surfacing so that the miners do not get UV Keratitis.

2.2.10 RS shall provide shielding (helmets) to protect miners from falling debris during transit.

Rationale: To protect miners from any dust or debris liberated during ascent.

2.2.11 RS shall include tight-fitting clothing for the occupant.

Rationale: Loose sleeves and other clothing components can snag on critical equipment or become entangled in the vehicle itself.

2.2.12 RS shall provide capability for hydration in transit.

Rationale: Long transit times and hot, humid conditions could lead to dehydration and thermal fatigue during ascent, especially if the EV becomes stuck.

2.2.13 Hoist system shall be certified for personnel lifting and be rated to lift the vehicle and any auxiliary equipment. Governors or preventers shall be incorporated to prevent the hoist system from loading the vehicle beyond its capacity. For example, the hoist system shall include components to prevent free-fall, provide automatic braking, and load check valves (hydraulic systems).

Rationale: Failure in the hoist system could cause personnel injury or death.

2.2.14 Hoist system shall be able to hoist the EV with the miner with no interaction from the EV occupant.
Rationale: Miner may become incapacitated during lift.

2.2.15 Hoist system shall include a force measurement capability in the hoisting mechanism.
Rationale: Operator must monitor the force in the hoist so as to have enough winching force to break through any snags, but don't want too much force to break the vehicle or the hoist.

2.2.16 During the preliminary design phase, designers shall perform a hazard analysis and failure modes analysis, consequences, and mitigations for the overall rescue system.
Rationale: System safety analysis helps figure out the hazards that drive the design. Once a preliminary design is in place, the analysis identifies what can go wrong and ensures the maturing design addresses those potential issues.

2.2.17 An overall rescue system test and checkout procedure shall be documented. At least one test run of the EV in the shaft with simulated mass (EV occupant, protective equipment, water, and supplies) shall be performed before any miner is loaded in the EV.
Rationale: Many unanticipated design deficiencies are discovered during initial operations of new systems. If there are critical flaws in the system's design that will be immediately encountered during operation, they should be discovered in tests that don't endanger human lives.

3 Additional Design and Operational Considerations

This section provides recommendations based on NASA expertise and experience that might be considered as solutions to some of the design problems for the miner rescue system and its associated components. Training and other operational considerations are also suggested. The additional recommendations are *not* listed in priority order.

3.1 Consumables need to match extraction time estimates with sufficient margins in case of delays.
Rationale: Delays in hoisting will expend consumables and will be difficult to anticipate.

3.2 If the EV exterior is a hard shell, removable panels in the shoulder region are a potential design solution for EV occupants with large shoulders. Additional protective clothing would be needed for this configuration.
Rationale: There may be miners that require extra EV volume in the shoulder region.

3.3 Consider having an upper surface with a shape to help collect any falling debris, thus preventing debris from falling into the narrow space between the vehicle and the tunnel wall causing damage to the EV or causing it to become stuck.

Rationale: Falling debris can become trapped or wedged between the vehicle and the wall.

3.4 Rescue system designers should consider including a "kill switch" that the occupant can use to immediately stop ascent. The kill switch needs to be capable of being locked out and reset from the surface.
Rationale: The occupant will have visual and other sensory feedback from the system (vibrations, audible scrapes, etc.), and may be able to prevent jamming or other system failures. The occupant may use the kill switch and then lose consciousness. Noise levels in the escape shaft during ascent may inhibit use of audio communications.

3.5 EV design should also incorporate features to allow lateral flexibility or some degree of bending along the length axis to minimize friction and the potential for becoming stuck (for example, pivot/flexible joints along length). Use of appropriate materials could increase lateral flexibility in the EV.
Rationale: A vehicle with flexible joints shortens the rigid length and allows the vehicle to traverse through tunnel imperfections (protrusions, etc.).

3.6 Wireless is preferred transmission method; if wireless communication is not feasible, consider integrating the transmission cable and rope.
Rationale: Otherwise, the cable for communication and telemetry is susceptible to tangling and snagging, and would have to be reeled in and out.

3.7 Consider incorporating a multiplexer for various monitoring devices.
Rationale: A single channel may not be able to transmit all the monitoring data to the surface.

3.8 If batteries are used, the EV should use one of the following battery chemistries: lead-acid (sealed) or Nickel-Metal Hydride. Use of Li-Ion batteries is only recommended if power requirements are sufficiently high and available space on EV volume is limited.
Rationale: Li-Ion battery cells present a significantly more volatile safety risk in high heat environments with inadequate cooling.

3.9 Manufacture or procure extra EVs and other critical hardware.
Rationale: Provides redundancy in case something happens to the first unit. Additional copies of the EV may also speed rescue time because one EV can be serviced while another EV is being utilized to extract a miner. For the entire rescue system, additional spare parts may be stockpiled such as: batteries, cameras, cables, and any protective panels or parts that are likely to be worn out or suffer collateral damage.

3.10 If a larger paloma-type device is above and connected via an umbilical to the EV, include a camera looking down on the EV to help make a judgment on how to free a stuck EV. If bandwidth is limited, this camera may be used only if needed.
Rationale: The extra camera would allow a quicker assessment of a stuck EV.

3.11 Consider sending down an emergency medical technician or other personnel to aid in loading EV and to be the last person evacuated.
Rationale: Trained medical technicians and EV operators would facilitate miner extraction.

3.12 A procedure should be developed to verify the safety of the system establish rules, procedures for contingencies, and train all people involved in the rescue. Training and procedure development can start well before the escape shaft is complete. Recommend setting up a practice facility and using actual operators and getting miners similar to those trapped to volunteer as surrogate evacuees.
Rationale: All personnel need to be trained for emergency actions and contingency operations.

Nomenclature or Glossary

CG Center of Gravity
EV Escape Vehicle
RS Rescue System