U.S. SOCOM Grand Challenge #3: NREL Technical Roadmap for a Man-Portable Power Supply System for TALOS

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-5D00-65985
June 2016

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303-275-3000 • www.nrel.gov

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Executive Summary

This NREL Technical Report was prepared as a part of the Grand Challenge #3 event organized by BMNT Partners, Inc. on behalf of U.S. Special Operations Command (SOCOM). The purpose of this document is to propose a technical roadmap for power supply technology to power the Tactical Assault Light Operator Suit (TALOS), an armored, powered exoskeleton for a SOCOM operator, which is currently in development at SOCOM with the first article prototype scheduled for delivery in August 2018.

Because TALOS' power supply system must meet size targets similar to the size of a large backpack while providing significant electrical power for an entire mission cycle without resupply, it requires a technology with both very high power density and very high energy density, which is very challenging to meet in practice. In addition, because it is closely coupled to the operator's body, common power supply limitations such as heat generation, noise, vibration, and exhaust are much less acceptable than in traditional vehicle applications. Technology capable of meeting these aggressive targets is not available on the market today, and therefore must be developed as a part of the TALOS vision. Because of these challenges and the short development timeline, we propose a staged development path based on three fundamental technical approaches: A combustion engine + battery approach (Technical Approach A), an H2 fuel cell + battery approach (Technical Approach B), and an advanced battery approach (Technical Approach C).

Due to fundamental limitations of combustion engine technology, Technical Approach A is only barely capable of meeting TALOS' minimum power and energy targets, and the exhaust, noise, vibration, and heat generated by the engine are likely to significantly limit TALOS' tactical applications. However, because it is the only technology capable of powering TALOS in the near term (<2 years), we propose that a TALOS power supply based on Technical Approach A be developed as an initial prototype to enable testing and modeling of the entire TALOS system.

Both Technical Approach B and Technical Approach C require longer development time and more technical risk, but are much more promising in the long term. Technical Approach C (Advanced Battery) is the most promising to meet all targets in the long term, but has long development time, high technical risk, and may turn out not to be viable. We therefore propose parallel pursuit of both Technical Approaches B and C to determine which is more viable. This Technical Report presents a preliminary design for a power supply based on each of the above three approaches, as well as a proposed development procedure for each.

In addition, we also propose development and continued use of a thermal and energy modeling software system for TALOS. This model can be developed alongside the Technical Approach A prototype, and can be used as an input to the development of each power supply stage. It will mitigate risk and reduce development time of each stage and allow the effects of new power supply technology on TALOS' capabilities to be quickly assessed.

By following the technical roadmap proposed in this document, a TALOS power system can be constructed and deployed even while more advanced stages are being developed. The result will be a TALOS system with capabilities and tactical use cases that improve and expand at each stage, ultimately reaching the stringent capabilities in about 10 years. In addition, the parallel

development of advanced technologies and software modeling will increase flexibility and mitigate technical risk. Finally, the technologies developed as a part of this program will have value in a variety of other applications, including other man-portable power systems, vehicles, and mobile devices.

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Introduction and Problem to be Solved

Introduction

This document proposes three potential technical approaches to meeting the targets for the Tactical Assault Light Operator Suit (TALOS) power supply system as a part of the TALOS Grand Challenge. While the primary purpose of this document is to specifically address the challenge of developing a power supply system to meet the targets of TALOS, we also briefly address related challenges in other man-portable power applications.

Because of the very challenging nature of the problem and the technical risks associated with the approaches, the NREL Grand Challenge team has chosen to propose three possible technical approaches rather than a single approach. A set of possible technical approach ideas were developed in brainstorming sessions that included subject matter experts (SMEs) from a variety of applicable technical disciplines. The resulting ideas were then refined through literature review, brief design processes, and further consultation with SMEs to produce the technical roadmap in this document. The roadmap is based on the technology approaches deemed most promising to meet the technical and logical targets presented by powering TALOS in the field during U.S. special operations assault missions.

This document will start with an exploration of the nature of the challenge facing the development of a power supply system capable of meeting TALOS' targets. The three proposed technical approaches (Technical Approaches A, B, and C) will then be presented, including a summary, design, pros and cons, technical risks, and proposed development path for each. We then list other approaches or technologies that were considered and rejected for inclusion in the roadmap, along with a brief description of why they were rejected. Finally, we summarize the proposed technical roadmap for development of the TALOS power supply system, and draw conclusions on the challenges and possible solutions for man-portable power supplies in general.

Problem Statement

The objective of this Grand Challenge is to develop a set of near-future viable technical approaches to the creation of a man-portable power system to support the targets of the TALOS or similar applications.

TALOS is a USSOCOM initiative to develop a powered, armored human exoskeleton designed to protect its operator during special operations missions in austere environments. In order to do so, TALOS must support its own weight, provide a comfortable body climate to its wearer, and meet Special Operations Forces (SOF) mission objectives in terms of audible noise and thermal signature. The tasks to be powered include walking/running, navigation, illumination, communication, processing, and kinetic movement.

In order to provide its intended functions, TALOS must have an on-board, man-portable power system capable of powering all of the above tasks. In order to enable NREL to perform preliminary design and make technical recommendations in this report, we have assumed a set of technical targets for the TALOS power supply system. We assume that the power supply system must, at minimum, be capable of providing 3 kilowatts (kW) of electrical power on a 48 VDC bus for duration of at least 10 hours of continuous operation without resupply. We will also consider a more stringent set of targets of 6 kW of electrical power for a period of 12 hours of continuous operation.

This assessment also assumed a peaking power target, which is that TALOS should be capable of providing double its continuous electrical power (6 kW minimum, 12 kW for the stringent targets) for a short period of time (to be determined). The power supply should be quiet and fit into a large backpack, for which NREL assumed a 40 liter maximum volume and a weight of no more than 100 lb.

It is anticipated that the development of the TALOS power system may require integration with other components of TALOS, and may require the use of consumable components. Due to the very challenging nature of the above assumed targets, it is expected that new power technologies must be developed to meet them (that is, low-TRL technologies will be considered). In addition, technical approaches capable of meeting a subset of the above targets may also be considered for similar applications. While safety and cost are considerations, at this point no promising technologies are prohibited.

Nature of the Challenges

Below we briefly discuss the targets listed above and how they affect the power supply system design.

Volume and Weight

The TALOS power supply system must be carried on board the (roughly man-sized) TALOS suit. It is therefore required to be both light and compact, about the size of a large backpack. In particular, NREL assumed a volume of less than 40 liters, and a weight less than 100 lb. As we will discuss below, this renders the high power and energy density targets of TALOS very challenging to meet.

Base Power/Energy

The first and possibly most challenging target for the TALOS power supply is its "base power/energy" target. These are defined as "minimum" and "stringent" targets, both of which will be addressed in this document. The minimum base power and energy targets are that the TALOS power supply must be capable of supplying at least 3 kW of DC electrical power continuously for a period of at least 10 hours (for a total of 30 kWhr of stored work). The stringent requirements assume a base of 6 kW electrical power for 12 hours, for a total of 72 kWhr of stored work. For comparison, 3 kW is about the amount of power required to heat and light a large home, while 6 kW would heat and light a small office building. Thirty kWhr of stored work is about that required to drive a 30-mpg car for about 132 miles, while 72 kWhr would drive the same car about 315 miles.

It should be observed at this point that the problem of supplying the above base power and energy targets for TALOS is a "kilowatts for hours" problem. Meeting the targets (especially the stringent targets) in a power supply system that can fit into a backpack requires both high power density and high energy density simultaneously. This is a challenging combination of targets to meet because, in general, technologies with high power density have low energy density and vice-versa. Other man-portable power problems might have a different category of targets, e.g.

“watts for days/weeks” would require very high energy density but not high power density, while “hundreds of kilowatts for seconds” would require very high power density but not high energy density. As we will discuss below, technology approaches that are appropriate to TALOS’ “kilowatts for hours” problem may not be appropriate for other types of man-portable power problems (and vice versa).

Another way to think of the TALOS base power/energy problem is by comparison to a human body (of which TALOS prototypes are about the same size): A walking, healthy adult human averages slightly more than 0.1 kW of base load power. TALOS requires packing substantially more power on a near-human frame than a human body can provide, which is challenging because a healthy human body is actually fairly powerful for its size. The main saving grace is that TALOS is only required to maintain its base power level for a few hours, while a human body must maintain it continuously (given proper diet and sleep). All of the solutions below take advantage of the limited time window of activity required of TALOS, and are not capable of continuous operation.

Peaking Power

In addition, TALOS has a “peaking power” target; that is, its power supply must be capable of surging to power levels much higher than the base power for short periods of time. In particular for the purpose of this evaluation, NREL assumed TALOS minimum peak power target of 6 kW and a stringent peak power target of 12 kW. While no specific peak power duration or frequency is specified, we assume that TALOS should be able to operate at peak power for a similar duration and frequency to its operator. A healthy human body is capable of surges up to about a kilowatt of work (ten times its base power), but can only maintain it for a few minutes, after which a period of rest is required (and therefore TALOS should be capable of the same). While the assumed TALOS targets as defined have a fairly low peak-to-base power ratio (peak power is only double base power), they still necessitate either oversizing the base power supply system or adding a second power system to handle the peak load only. Both of these approaches are used in the technical approaches presented in this document.

Thermal

Because TALOS requires much more power than that of a human body to be packed onto a human frame, the management of the resulting heat is critically important to its operation. The TALOS power supply system has two main thermal targets: an operator comfort target and power plant temperature range target. While these targets serve different purposes, they are all critically dependent on the rate of heat generated by the power plant itself. While no specific maximum heat rate is given in the targets and the design of the TALOS thermal system itself is beyond the scope of this document, we estimate the heat rate of each proposed power supply technical approach and discuss how it affects each thermal target.

First, it is necessary that the internal suit climate experienced by the human operator of TALOS be maintained at an acceptable comfort level. In addition to reducing physical performance and comfort, increased body temperature of the human operator reduces cognitive performance, which is unacceptable in a combat situation. Therefore, TALOS must be capable of maintaining its internal operator temperature at a comfortable level, which requires rejecting both the operator’s own body heat and the heat generated by the suit into the atmosphere without allowing it to unacceptably heat the operator.

Second, the power supply system itself has a specified temperature range of operation, which must be maintained to avoid damage to or shutdown of the power supply. This temperature range is different for different technologies, but ultimately all heat generated by the power supply must be vented to the atmosphere without allowing the temperature of the power supply itself to rise above its acceptable operating range. In addition, if the temperature range of operation of the power supply is substantially above the user's body temperature, then the two must be sufficiently thermally insulated.

Noise/Vibration

Because of the power supply's proximity to the TALOS operator, noise and vibration generated by the power supply (for instance, due to a reciprocating engine) will be distracting and tiring to its operator. Many power supply systems are reciprocating (such as internal combustion engines), or contain air blowers or cooling fans, all of which generate noise. While it is possible to add mufflers to some kinds of engines, this adds weight and size and reduces efficiency. The TALOS seeks a tactically quiet source of power, which may not be possible with some of the technologies presented in this document. While no specific numeric vibration target is given, we estimate the likely effect of the noise and vibration generated by each power supply technical approach below, and its likelihood of meeting the noise and vibration targets.

Environmental

TALOS is intended to operate in highly uncontrolled combat environments (e.g., tight spaces, and extreme weather/temperature conditions). Inability of the power supply to function in these environments limits its tactical usefulness. For each power supply, we discuss its ability to operate in each of these assumed combat environments.

Safety

Finally, dense power and energy often means the possibility of accidental energy release. Since the TALOS power supply must be worn near a human body (and in the presence of other people) and operated in a hostile environment, the possibility of energy release or exposure to unsafe conditions must be a consideration for the TALOS power supply. For each power supply technology approach in this document, we briefly discuss any hazards introduced by the power supply and their severity.

Technical Approach A: Combustion Engine + Peaking Battery

Summary

The first technology approach we propose for the TALOS power supply system is based on a combustion engine combined with a peaking battery. While the individual technologies in this approach are quite mature (most are decades old), this particular application is new and therefore will require new packaging and thermal management design. Because it involves little research and implementation using commercial off-the-shelf components, this approach has the shortest development time to reach TALOS’ minimum targets. However, it is plagued by unavoidable heat, noise, and vibration issues, and its power and energy density levels limit it to meet the assumed minimum and stringent targets. Therefore, while it is the least technically risky and has the shortest development time, it is also least promising in the long run to meet all of the TALOS power supply targets, and would probably limit TALOS’ tactical usefulness.

Design

The energy flow structure of a power supply designed using Technical Approach A is shown in Figure 1 (specs listed for NREL assumed minimum TALOS power/energy targets). In this approach, a gasoline internal combustion engine (GICE) is fueled from a small gasoline tank. The engine drives a torque shaft, which is connected to a DC alternator/generator. The GICE / alternator combination produces slightly more than TALOS’ base power (3.6 kW target minimum, 7.2 kW for the stringent requirements, equivalent to about 75/150A) on a 48 V DC bus. Also connected to the DC bus is a 48 V Lithium-Ion (Li-ion) battery, which can discharge to supply the rest of the peak power (minimum/stringent target: 3.0/6.0 kW, another 62.5/125 A on the 48 V DC bus). The battery can also charge at 12.5/25 A from the alternator current during times when only base load is required, because 75/150 A capability of the alternator minus 62.5/125 A base load current leaves 12.5/25 A available to charge the battery.

Observe that there are no power electronics present in this design: the voltage regulation of the DC bus is provided solely by the battery, and the actuator loads are required to be able to operate across its entire voltage range from discharge near empty (~40 V) to peak charging (~60 V). A small DC/DC converter to regulate a lower voltage DC bus for communications, sensors, and computation may be necessary, but its power rating (and therefore its size) should be kept to an absolute minimum.

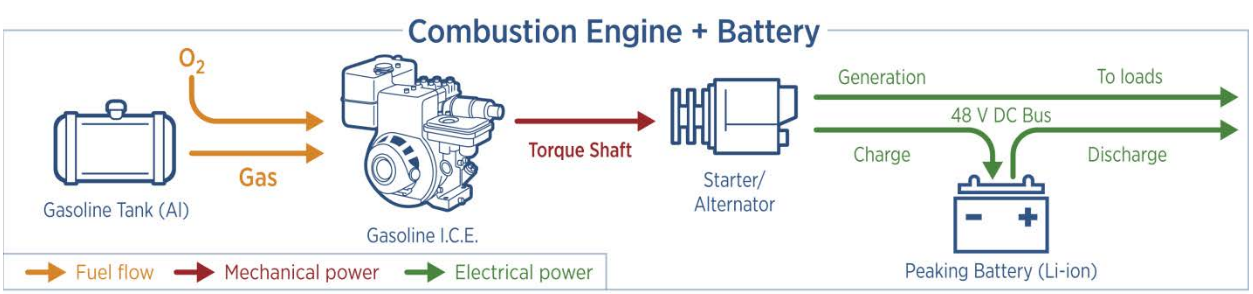

Figure 1. Energy flow diagram for combustion engine + peaking battery approach.

We discuss the targets for each component of this design; estimate its size, weight, and characteristics; and analyze the performance of this power supply design below.

Gasoline Internal Combustion Engine (GICE)

For this power supply design, we select a four-stroke GICE due to its high power/weight ratio, (relatively) high efficiency, energy dense fuel, and technology maturity (discussion of other fuels/engine types and reasons for rejecting them can be found below). A two-stroke engine may also be considered for its lighter weight, but its lower efficiency would exacerbate thermal problems and require more fuel. The minimum required 3.6 kW mechanical shaft power is equivalent to about 4.8 horsepower, about the size of a push-lawnmower engine. The stringent target of 7.2 kW mechanical shaft power is equivalent to about 9.7 horsepower, about the size of the engine on a riding lawnmower or gasoline-powered golf cart. Four-stroke gasoline engines scale well to this power range, thus their ubiquity in applications at this power level.

There are commercial off-the-shelf engines that meet these targets. Based on commercially available parts, we estimate the weight of a 4.8 horsepower, four-stroke gasoline engine at about 20 lb. Similarly, we estimate the mass of a 9.7 horsepower, four-stroke gasoline engine at about 50 lb. While each of these engines contains some systems that would not be necessary for TALOS (such as an internal starter and a gas tank), this technology is mature enough that there is little room for improvement on these commercial engines.

Gasoline Tank

Gasoline is a fairly energy dense fuel, with an average lower heating value of about 42.4 MJ/kg and a density of about 0.77 kg/L. Because our purpose is to attempt the best possible implementation of a combustion-based technical approach, we will (generously) assume a chemical-to-work efficiency for the GICE of about 20%. Under this assumption, to meet the minimum stored work target of 30 kWhr (108 MJ), we require about 12.7 kg (28 lb), 16.5 L of gasoline. For the stringent stored work target of 72 kWhr (259 MJ), we require about 30.6 kg (67 lb), 39.7 L gasoline. Notice that even under our generous efficiency assumption, the gasoline alone for the stringent target takes up almost the entire 40 L of allowed power supply volume.

An aluminum gasoline tank is a reasonable compromise between the high weight of a steel tank and the low safety margins of a polyurethane tank. Aluminum gas tanks typically weigh about 0.5 kg per liter of fuel, which yields a full tank weight of 21 kg (46 lb) for the minimum energy target, or 50.4 kg (111 lb) for the stringent energy target. Observe that the full tank weight for the stringent energy target alone is more than the allowed weight for the entire power supply system. Again, because of the maturity of the technology and the basic physics involved, there is little opportunity to improve upon common commercial gas tanks.

Starter/Alternator

A DC alternator is necessary to convert the mechanical torque on the engine shaft to DC electrical power. In addition, the alternator may be selected so that it can be run in the motoring mode, allowing the same device to be used to start the engine from stall. This alternator must operate at the selected DC bus voltage (48 V) and be capable of providing the necessary current to simultaneously provide the TALOS power load and slowly charge the battery (75 A minimum/150 A stringent).

Again, alternators are a mature technology that is commonly used in automobiles, boats, and many other applications. While the assumed TALOS DC bus voltage (48 V) is higher than those of most automotive alternators (usually 12 V or 24 V), alternators can be easily wound for the 48 V voltage level and are comparably sized to 12 or 24 V alternators of the same rated power level. Based on commercially available parts, we estimate the weight of the minimum required 48V, 75 A alternator at about 25 lb., or about 50 lb for the stringent 48V, 150 A alternator.

Peaking Battery

The last major component of the power supply system following Technical Approach A is the peaking battery. We select a 48 V Lithium-ion battery, rated at 7.5 ampere hours (Ahr) for the energy target, or 15.0 Ahr for the stringent energy target. While a lead-acid battery might be used and would provide higher surge currents, the relatively low peak-to-base power target allows a Li-ion battery at this energy rating to provide the difference between peak and base power, and a Li-ion battery will be much more energy dense.

Again, the assumed TALOS DC bus voltage of 48 V is higher than the 12 or 24 V used in most automobiles, but a Li-ion battery can be constructed to provide the 48 V bus level at approximately the same weight and size as 12 or 24 V batteries at a similar power level. Typical li-ion batteries on the market today have a specific energy of about 0.18 kWhr/kg and an energy density of about 0.4 kWhr/L. We select a 7.5 Ahr battery for TALOS' power/energy, and estimate its weight and volume at 2.0 kg (4.4 lb), 0.9 L. This battery should be capable of discharging at 62.5 A (8.3 C, that is, 8.3 times the one-hour-discharge current), which allows it to provide up to 3.0 kW of DC electrical power during peaking power surges, which in combination with the 3.0 kW from the GICE/alternator can meet the assumed 6.0 kW peaking power surge target for TALOS, and can provide this peaking power for up to about 4 minutes without recharging, after which it must be recharged from the GICE/alternator at 12.5 A for 36 minutes to reach full charge. If the peaking power surges come at rapid intervals or are particularly long, the battery may require active cooling (such as a liquid heat exchanger) to avoid overheating.

Because power rating and energy rating of a battery are both roughly proportional to weight/volume, we then estimate that the 48 V, 12.5 Ahr battery required to meet the stringent peaking target should have weight and volume of about 4.0 kg (8.8 lb), 1.8 L. Its maximum discharge and charge currents are 125 A and 25 A respectively, and its charge and discharge time characteristics are roughly equal to those above (4 minutes peak discharge, followed by 36 minutes recharging, assuming peaking surges to 12 kW).

Design Totals

The total weight of the major commercial off-the-shelf components selected above for the assumed minimum power/energy targets for TALOS is about 43.4 kg (95.6 lb), just under the targeted 100 lb maximum. Careful integration and packaging will be required to meet the target mass and volume requirements while maintaining acceptable thermal performance.

However, the total weight of the components necessary to meet the assumed stringent power/energy targets is about 95.3 kg (210 lb), vastly more than the maximum allowed. Since all of the technologies involved are quite mature (and therefore unlikely to dramatically improve in power and/or energy density), it is very unlikely that it will be possible in the foreseeable future to meet the stringent targets using a combustion-based power supply system. These technologies simply lack the very high power and energy density necessary to meet the stringent targets.

Technical Approach Characteristics

Below we analyze the practical characteristics of the above proposed TALOS power supply design, and consider its ability to meet TALOS' tactical targets.

Thermal Management

The GICE used to provide the TALOS base power in Technical Approach A generates significant heat through gasoline combustion. In our analysis, we will generously assume approximately 20% thermal-to-work efficiency for the combustion engine, which means that the remaining approximately 80% of the combustion energy is released as heat. At TALOS' assumed minimum base power (3 kW mechanical), this results in a heat rate of about 12.0 kW thermal. In addition, at peak power the Li-ion battery contributes an addition 2.0 kW, raising the total to 14.0 kW. Since the engine operates at a much higher temperature than a human body, significant thermal isolation between the engine and the operator will be necessary.

The total heat rate produced by the power supply is about 140 times the heat rate of a human body and would be sufficient to heat a large building on a cold winter day. Fortunately, as in an automobile, much of the heat is carried away by the exhaust, but a substantial cooling system including a large radiator and cooling fans will be required to prevent overheating of the operator and/or the engine itself.

Noise and Vibration

The GICE is a reciprocating engine, which by design generates pressure waves with each cylinder ignition, resulting in both noise and vibration of the engine itself. It is possible to mitigate both of these effects, but at a cost. Mufflers reduce the noise produced by the engine but add weight and volume, and reduce the efficiency of the motor. Similarly, reactive motor mounting can reduce vibration felt in the suit chassis, but again at the cost of additional weight and volume and reduced efficiency. In addition, the large cooling fans necessitated by the thermal system must move a significant volume of air, which also generates unavoidable noise. More detailed design, modeling, and analysis will be necessary to determine the extent to which it is possible to mitigate the effects of the noise and vibration created by the combustion engine.

While careful design of the motor mounting, muffler, and fans can reduce noise and vibration, these effects are fundamental to combustion engine technology, and the ability to mitigate them is limited. Existing systems that contain combustion engines at the power level required for TALOS (such as lawnmowers, leaf blowers, gasoline-powered golf carts, etc.) are well known to be noisy. Similarly, it is very unlikely that a TALOS power supply system based on combustion engines will be capable of meeting SOF mission objectives in terms of audible noise and heat signature. In addition, the vibration generated by a combustion engine so closely coupled to the operator's body is likely to be a significant distraction, and may even limit the time that an operator can comfortably operate the suit.

Environmental

The primary environmental limitations of a TALOS power supply system based on Technical Approach A come from the combustion engine. First, all combustion engines are air-breathing (oxygen is required for the combustion in the cylinders), which is an environmental/operational limitation. This means that they must also intake a significant quantity of air (air filtration systems are now advanced enough to allow them to operate even in environments with high atmospheric dust or contaminants). In addition, combustion engines have long been shown to be robust enough to operate even in the most extreme weather conditions. However, because they produce a significant quantity of exhaust, which contains carbon monoxide, carbon dioxide, and other toxic or anoxic gases, it is not safe to operate combustion engines in confined spaces.

Safety

The most significant safety hazard to either the operator of TALOS or nearby personnel introduced by Technical Approach A is the emissions produced by the combustion engine. While the system should be designed to vent the exhaust in such a way to minimize the operator's exposure, because the engine is so near to the operator's head, it will likely be impossible to ensure that exhaust is not blown back near the operator's nose or mouth. In addition, operation of the TALOS indoors or in tight spaces is likely to expose the operator or other nearby personnel to potentially toxic levels of carbon monoxide, carbon dioxide, and other combustion gases.

While carrying highly combustible gasoline is a fire hazard, in general this risk has long been considered acceptable for both military and civilian purposes. If the gasoline tank is damaged or subjected to small arms fire, then liquid gasoline may coat the ground or the suit itself, and may become ignited. Therefore, it is possible that the risk of gasoline fires may be a greater threat to the TALOS operator than to occupants of a traditional gasoline-powered vehicle because the flame is likely to be nearer the occupant and the chance for escape more limited. Further study is needed to assess this safety hazard.

In addition, some Li-ion batteries have been known to combust when damaged and exposed to air. However, improved packaging technologies have significantly reduced this risk, and the small size of the TALOS battery probably renders this risk small. Li-ion batteries have already been approved by the U.S. military to be carried on the body of a soldier (as in the conformal battery).

Comparison: Push-Lawnmower Engine

A useful comparison to understand the likely characteristics of a TALOS power supply system based on Technical Approach A is to the engine of a gasoline-powered push-lawnmower, which is quite similar. Considerations with regard to a push-lawnmower engine include the following:

1. How noisy is a push-lawnmower when used?
2. Is it hot to the touch?
3. Do you get a headache or nerve discomfort from using it for more than an hour or so (due to noise and vibration)?
4. Could it run under water?
5. Would you run it indoors (even without the big spinning blade)?

While the effects of noise, vibration, heat, and exhaust of a combustion engine can be mitigated to some extent, they are fundamental limitations of the technology. To get around them, it is necessary to go to a fundamentally different technical approach.

Pros/Cons

The primary advantages of Technical Approach A are the maturity of its component technologies and its low development time. Each of its components is available commercially today, and only careful thermal design, packaging, and integration are required. It is the only technical approach presented in this document that is likely to be fieldable within two years, and little research is required to implement it.

However, Technical Approach A is also the most limited approach to the TALOS power supply system in the long term. It is limited by its power and energy density to be capable of meeting only TALOS' assumed minimum power and energy targets, and is very unlikely to ever be capable of meeting the stringent power and energy requirements. In addition, it is very unlikely to be capable of being tactically relevant with respect to noise and vibration of the suit due to the reciprocating engine, which may be distracting and uncomfortable to the operator. Finally, because it is air-breathing, the combustion engine is operationally and environmentally limited.

As a result of the above limitations, a TALOS system using a power supply system based on Technical Approach A is likely to have limited tactical application. However, such a TALOS system may still have application to other mission types, such as disaster response and rescue. In addition, as we discuss in the summary of our technical roadmap, development of a TALOS power supply based on Technical Approach A would allow an initial TALOS prototype to be constructed and tested, which would allow field testing of other TALOS subsystems and model validation, and thereby contribute to the overall technical roadmap. Therefore, we propose that a TALOS prototype with a power supply based on Technical Approach A be developed as a stepping-stone to later prototypes based on the more advanced power supply systems discussed in Technical Approaches B and C below.

Proposed Development Path

Because the constituent components exist and are commercially available today, the primary challenges to implementation of a TALOS power supply system based on Technical Approach A are packaging, integration, and thermal design. We propose that TALOS power supply development start with a complete thermal modeling of the TALOS suit. In parallel, we propose the design and integration of the appropriate G.I.C.E, fuel tank, alternator, and battery, most likely performed by an established engine manufacturer. We estimate 1 year for completion of the thermal modeling and power system design tasks. In a second year, the power supply system would be integrated with the TALOS suit, and a power supply control system and a thermal management system for the TALOS suit developed and integrated. Finally, a prototype of the TALOS suit with integrated power system would be constructed and tested. NREL has extensive capabilities in thermal modeling and design, power system control, and an advanced power system test facility on-site. Estimated time to construct the working prototype is 2 years.

In addition, because TALOS' thermal and energy use characteristics are so important for its operation (and because they represent significant technical risk), we recommend the development of a software thermal and energy modeling system for TALOS. This software modeling system can be developed in parallel with the development of a power supply system based on Technical Approach A and be validated based on the resulting power supply performance. It should represent the energy use profiles for selected set of missions for TALOS, along with how the performance of the power supply system and thermal management system affect TALOS' mission performance. The resulting modeling system will assist in power supply and thermal management system development and performance testing, mitigate technical risk, and reduce development time.

Technical Approach B: H2 Fuel Cell + Peaking Battery

Summary

The second technical approach we propose in this document is based on a hydrogen- (H2-) powered fuel cell. This approach avoids many of the limitations of Technical Approach A by avoiding the use of a combustion engine. In addition, it reduces the parts count by sizing the fuel cell for the peak power target, increasing the fuel cell efficiency at base load. While the technologies involved are less mature (and therefore of higher technical risk and with longer development times), this approach is capable of easily meeting the assumed TALOS minimum power and energy targets using a standard air-cathode fuel cell. It may be possible pursue one of several advanced fuel cell cathode options, which can potentially meet the stringent power/energy targets.

As compared to Technical Approach A, Technical Approach B has fewer total parts (reducing weight and volume), has fewer moving parts and so produces less noise and vibration, and produces a much lower heat rate (although heat management will still be a challenge). To meet the power supply weight and volume targets, it is necessary to use cryogenically stored, atmospheric-pressure liquid hydrogen fuel, which requires miniaturization of existing vacuum-walled hydrogen tanks. In summary, it has the potential to meet most (though not all) of TALOS technical and tactical targets with moderate technical risk and development time.

Design

An energy-flow diagram of a TALOS power supply system following Technical Approach B is shown in Figure 2 (specs are listed to meet the minimum power/energy targets). In Technical Approach B, we replace the combustion engine used in Technical Approach A with a H2-powered fuel cell, which feeds a 48 V DC load bus and is fueled by a cryogenic liquid-hydrogen (LH2) tank and atmospheric oxygen. The H2 fuel cell is sized for TALOS' assumed peak power target (6 kW minimum, 12 kW desired, equivalent to about 125/210 A on the 48 V DC bus). In addition, a Li-ion battery assists with peaking power and in meeting the high power ramp rates required for TALOS.

We have chosen to size the H2 fuel cell for the assumed TALOS peak power targets in order to take advantage of the peak-to-base power ratio and thereby place TALOS' base power at the fuel cell's most efficient operating point. H2 fuel cells generally reach their peak chemical-to-work efficiency (about 60%) at about 50% of their rated power level [1]. Because the peak-to-base power ratio specified for TALOS is about 2:1, this means that if the fuel cell is sized for the peak, then base power falls near the fuel cell's most efficient operating point. The same battery used in Technical Approach A is used here, primarily to meet TALOS' high power ramp rates and to extend the allowable peaking power duration. If either the ramp rates or the peak-to-base power ratio of the TALOS targets were changed, then the relative sizing of the fuel cell and battery should be reconsidered.

While most H2 fuel cells for automotive applications use compressed gaseous H2 storage, we have selected an atmospheric-pressure, cryogenic LH2 tank in which to store the hydrogen fuel for TALOS. This is necessary to meet TALOS' energy storage target within the allowed weight and volume, though it also presents other challenges such as LH2 boil-off (discussed below). The reasons for rejecting other possible hydrogen storage methods (such as compressed gaseous hydrogen or metal hydrides) are discussed later in this document.

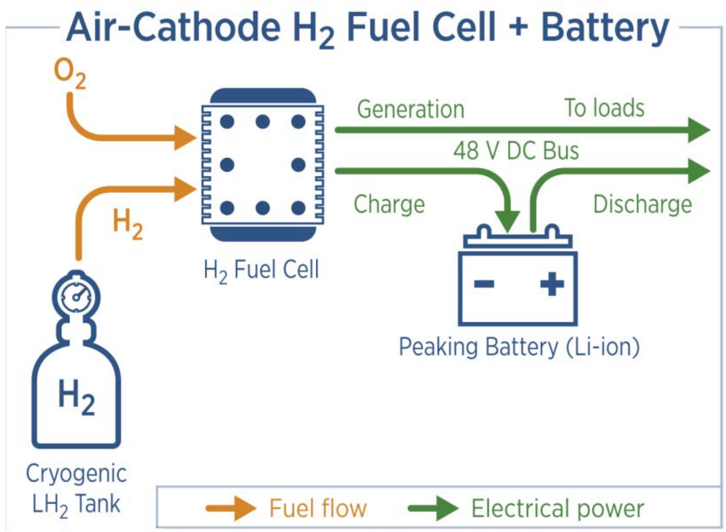

Figure 2. Energy flow diagram for fuel cell + peaking battery approach (air-cathode).

Notice again the lack of power electronics in this design. This design decision avoids the mass, volume, and reliability issues associated with a DC/DC converter, but it creates the target that the actuator loads must be capable of handling the fuel cell's entire operating voltage range. While this voltage range can be tuned, the voltage at peak power is generally about half of that at open circuit [1]. Again, a small DC/DC converter may be used for communications, sensors, and computation, but should be kept to the minimum power rating possible.

The design presented below is based on the assumption of using an air-cathode fuel cell, in which atmospheric oxygen fuels the fuel cell cathode, requiring a cathode air blower and rendering the TALOS power supply system air-breathing. As we show, it is possible to meet TALOS' power and energy target using this design, but not the assumed stringent power and energy targets. The most direct path to meeting the stringent target is to instead to go a pure-O2 cathode fueled by cryogenically stored, atmospheric-pressure liquid oxygen (LO2). This significantly reduces the fuel cell volume, increases its efficiency, and eliminates the need for a cathode air blower. However, it also requires the addition of a second fuel tank (the LO2), which adds its own volume and (more significantly) another consequential safety hazard, since pure O2 is quite volatile. We believe this to be the most direct path to reaching TALOS' stringent power and energy targets using a fuel-cell-based power supply, but will probably extend the development time (because pure-O2 fuel cells are less mature), and the safety concerns associated with carrying pure LO2 should be carefully investigated.

We describe each of the components of the design in Technical Approach B below (assuming an air-cathode H2 fuel cell), along with their characteristics, weight, and volume.

Air-Cathode H2 Fuel Cell

Air-cathode H2 fuel cells have undergone quite a bit of development in the past two decades, mostly with focus on automotive applications. The H2 fuel cell required for TALOS' power and energy targets (both assumed target and stringent target) are smaller than automotive fuel cells, but fuel cells have been shown to scale to lower power levels quite well. In addition to the fuel cell stack itself (where hydrogen and oxygen react to produce an electric current and water), the fuel cell also requires fuel lines, fuel pumps, an air-blower, a small battery to start the pumps and blowers, and the associated packaging.

These supplementary components are included in the "balance of system" mass and volume estimates (650 W/kg and 650 W/L [2]) published by the Department of Energy (DOE) Fuel Cell Technologies Office. Therefore, an air-cathode H2 fuel cell sized for the assumed peak power surge target (6.0 kW, 125 A on the 48 V bus) should weigh about 9.2 kg (20 lb) and occupy 9.2 L. For the stringent peak power surge of 12 kW, an 18.5 kg (40.6 lb), 18.5 L fuel cell is required. We estimate that this fuel cell should have a chemical-to-work efficiency of about 60% at base load (50% of fuel cell rating), and about 40% at peak load (equal to its rating) [1].

Cryogenic Liquid H2 Storage

Pure hydrogen fuel has a very high thermal energy density (120.0 MJ/kg lower heating value). However, it is gaseous at ambient temperature, even at very high pressure. Therefore, to make pure hydrogen liquid, it must be kept at cryogenic temperatures (less than 14 K, -259.2 C), and even then has fairly low volumetric density at atmospheric pressure (12.9 L/kg at 14 K and 1 bar).

Assuming the base power fuel cell efficiency of 60%, to meet TALOS' minimum stored-work target (30 kWhr, 108 MJ), about 1.5 kg of pure H2 fuel must be stored. For the stringent stored-work target (72 kWhr, 259 MJ), 3.6 kg pure H2 fuel are required. This pure H2 fuel is stored at cryogenic temperatures (< 14 K) in a vacuum-walled tank at approximately atmospheric pressure. Assuming a tank mass equal to that of the fuel it stores, then the LH2 tank required for TALOS' minimum energy target has volume of about 19.4 L and weighs 3.0 kg (6.6 lb) full, while the LH2 tank for the stringent stored work target has volume of about 46.4 L and weighs about 7.2 kg (15.8 lb) full. To our knowledge, this is a great deal smaller than any commercial LH2 tanks used today and must be developed as a part of the TALOS power supply system design effort. Obviously, the stringent stored work target cannot be met by this technology, since the volume of the required LH2 fuel alone is more than the allowed power supply volume of 40 L.

Since no refrigeration is present in the tank, the cryogenic liquid H2 fuel must be pumped into the tank and its temperature maintained by the very high thermal impedance of the tank walls. As the hydrogen heats, it expands and the pressure in the tank increases. Once it reaches the maximum acceptable pressure, hydrogen must be slowly vented to the atmosphere through a pressure value to maintain pressure in the tank. Since the TALOS LH2 tank is relatively small, its surface-to-volume ratio is fairly high, which limits its thermal impedance. Thus, the LH2 fuel cannot be stored in the TALOS tank for long periods of time; it must be pumped into the tank from another cryogenically refrigerated tank shortly before use. This creates a logistical challenge that must be addressed to ensure the availability of LH2 fuel for TALOS in the field.

While to our knowledge no LH2 tanks have been constructed at the scale required for TALOS, a simple estimate of the boil-off rate can be made by comparing the LH2 tank for the BWM Hydrogen 7, whose 114 L tank experiences no boil off until 17 hours after filling, to a state of complete boil off after 9 days [3]. Assuming that boil-off rate is approximately proportional to tank surface area and cylindrical tanks, we expect no boil-off from TALOS' 19.4 L tank until 10 hours after filling, and complete boil-off in just over 5 days. It remains to be seen if LH2 tanks can be miniaturized to the size needed for TALOS while maintaining the same per-unit-surface area boil-off rates.

Peaking Battery

Similar to Technical Approach A, in Technical Approach B a Li-ion battery is included to meet TALOS' high power ramp rates, and to assist with peaking power operation. As in Technical Approach A, we select a 48 V, 7.5 Ahr Li-ion battery, which should be capable of providing 3.0 kW of electrical power on the 48V DC bus (allowing the fuel cell to continue to operate at base power while providing the total peaking target of 6.0 kW) for about 4 minutes. After the battery is discharged, the fuel cell may continue to provide peak power by itself, but the duration of this mode of operation is limited by the temperature of the fuel cell (see the Thermal Management section below). Again, a larger (12.5 Ahr) battery capacity is required to meet the stringent power and energy targets. Therefore, we estimate a 2 kg (4.4 lb), 0.9 L battery for the minimum targets, and a 3.3 kg (7.3 lb), 1.5 L battery to meet the stringent targets.

In Technical Approach B, a passive-hybrid approach is used to combine the output of the fuel cell and battery. This eliminates the power electronics required for a more sophisticated approach, but means that the design of the fuel cell and battery must be coordinated so that their combined output (based on DC bus voltage) ensures that both devices operate within their limits [4].

Design Totals

The total mass of the combined full LH2 fuel tank and fuel cell required to meet TALOS' minimum power and energy targets is 29.5 L and 14.2 kg (31.3 lb), well within the allowed weight and volume for the TALOS power supply system. However, to meet the stringent power and energy targets, a 66.4 L, 29.0 kg (63.8 lb) power system is required. While the power supply system to meet the stringent targets is within the allowed weight, its volume is much too large, primarily due to the significant volume of the required LH2 fuel. Therefore, to meet the stringent TALOS power and energy targets within the allowed power supply system volume, it is necessary to go to an even more advanced fuel cell technology, such as one of those discussed below.

Advanced Cathode Options

We have shown above that it is not possible to meet the assumed TALOS power supply performance targets using existing air-cathode H2 fuel-cell technologies. The primary limiting factor is the volume of the stored H2 fuel necessary to meet the stringent energy target, and to a lesser extent the volume of the fuel cell itself needed to meet the stringent power targets. The primary driver of both of these effects is the cathode-side ionization reaction, where atmospheric O2 is ionized and reacts with protons moving across the proton membrane. Atmospheric O2 does not easily ionize, and a catalytic large surface area is required for the reaction, driving a large required volume of the fuel cell. In addition, the inefficiency of this ionization is the primary source of energy loss in the fuel cell, which results in more required H2 fuel to meet the stringent stored-work target. If this ionization process could be made more efficient, then the volume of both the fuel cell and stored H2 fuel would decrease.

One possible approach is the use of pure liquid O2 fuel (in place of atmospheric O2) as the cathode reactant, which would significantly increase the chemical activity of the cathode-side reaction, potentially both reducing required catalytic surface area and increasing efficiency. In addition, the cathode-side blower would be eliminated, further reducing fuel cell volume, increasing efficiency, and decreasing noise. A second liquid fuel tank would be required to store the required liquid O2 (LO2) fuel (adding its own volume and weight), but LO2 is much more dense than LH2, and therefore net volume might still be decreased (at the cost of additional weight). However, LO2 is highly volatile, and therefore its addition would add a potentially significant new safety risk.

A second possible approach to improvement of the cathode ionization process is the use of advanced catalyst structures, such as crystalline Pt_3Ni nanoframes [5]. By increasing the activity and the active area of the cathode catalytic surface, these advanced structures decrease required cathode volume and increase the efficiency of the O2 ionization reaction in the cathode, both of which serve to decrease the volume of the fuel cell and the associated fuel storage necessary to meet TALOS' stringent power and stored work targets. While these advanced catalyst technologies are still immature, they have potential to enable H2 fuel cells to provide greater power and energy within TALOS' allowed power supply volume.

Technical Approach Characteristics

Below we analyze the practical characteristics of a TALOS power supply design based on Technical Approach B, and consider its ability to meet TALOS' tactical targets.

Thermal Management

Like the combustion engine in Technical Approach A, the fuel cell in Technical Approach B consumes fuel to produce electrical work, and all of the chemical energy of the fuel not converted to work becomes heat. We will first analyze the heat rate produced by the fuel cell at TALOS' base load power, which falls near the peak fuel cell chemical-to-work efficiency of 60%. For TALOS' base power target of 3.0 kW, 2.0 kW of heat is produced, while for the stringent base power target of 6.0 kW, 4.0 kW is the resulting heat rate. This heat rate is significantly lower than that produced by the combustion engine in Technical Approach A, but is still enough to heat several rooms of a house. In addition, the fuel cell operates at a lower temperature (50 to 80 C) than a combustion engine, which renders its heat lower quality and therefore requires a larger radiator to reject such heat. Finally, the fuel cell does not have an exhaust plume to carry away much of its heat.

Further, consider the heat rate produced in the fuel cell during peaking power surges. While the battery maintains significant state-of-charge, the fuel cell operates at only slightly higher than base power (depending on the design of the fuel cell and battery). However, once the battery is nearly empty, peaking power can only be provided by the fuel cell operating near its rating, resulting in a chemical-to-work efficiency of about 40%. At the TALOS minimum peak power target (6.0 kW), about 9 kW heat rate is produced, and at the stringent peaking power target of 12.0 kW, 18 kW of heat is produced. These numbers are more similar to those produced by the combustion engine, but at lower temperature.

While no detailed thermal analysis was performed in this Grand Challenge effort, we consider it unlikely that a thermal management system can be designed for TALOS that is capable of continuously venting the heat produced during fuel cell peaking power to the atmosphere. As a result, during peaking power surges after the battery is empty, the temperature of the fuel cell will increase. Most H2 fuel cells are capable of operating up to about 90–95° C, above which the fuel cell may shut down or be damaged. In addition, fuel cell temperatures above 80° C usually results in decreased efficiency, which might lead to thermal runaway. Therefore, the frequency and duration of the peaking power surges are limited by the temperature of the fuel cell, which must be prevented from overheating by reducing activity to base power levels when temperature exceeds safe limits. In addition to being a limitation on the physical performance of TALOS, this also creates a cognitive burden on the operator, who must be aware of the fuel cell temperature and how it affects his activities. It will therefore be necessary to carefully design the thermal system and operator interface to minimize this cognitive burden.

While the fuel cell in Technical Approach B produces a lower heat rate at base load than the combustion engine in Technical Approach A, its heat is lower quality, and peaking power results in much more heat. Therefore, a heat exchanger, large radiator, and cooling fans will still be required to prevent overheating of the fuel cell and/or operator. Cathode evaporative cooling [6] should be considered for an air-cathode H2 fuel cell to reduce the required radiator size. Since the fuel cell temperature is lower, less thermal isolation is required between the operator and the power supply system than in Technical Approach A.

Noise/Vibration

Technical Approach B has few moving parts, which results in little noise or vibration. The fuel cell itself contains an H2 fuel pump, which generates minimal noise and vibration. The cathode air blower must move a significant quantity of air, which generates some noise, but careful design of the blowers can minimize this noise. Moving to a pure O2 cathode would add a second fuel pump for the O2 (which generates minimal noise), and remove the cathode air blower, probably resulting in a net noise reduction. Finally, the cooling fans necessitated by the thermal management system will generate some noise. Because vibration caused by the pump and fans is quite small, the distraction to the user should be minimal.

Environmental

While the H2 fuel cell in Technical Approach B consumes fuel, its only exhaust is water vapor (and a small amount of unspent hydrogen fuel), and therefore it is safe to use indoors or in tight spaces. If an air-cathode is used, then it is air-breathing and therefore cannot be used underwater. Like a combustion engine, it must intake air, but the air can be filtered to minimize contamination from atmospheric dust. Air-cathode fuel cells have been demonstrated in automotive applications to be operable in environments down to -40 C [7], and are generally considered robust to precipitation and extreme weather conditions. If a pure-O2-cathode is used, then no access to air is needed, and the power system can be used underwater (although a thermal management system not dependent on forced-air convection may be needed).

Safety

Pure H2 fuel is quite combustible (thus its high energy density in this application), and therefore may present a fire hazard. However, the fuel is not stored under pressure, and will vaporize rapidly if exposed to air, carrying away any flaming gasses and minimizing the possibility of explosion. Some experimental results on low-pressure LH2 tanks have shown the possibility of detonation under extreme conditions, but this is considered unlikely in practice [8]. A useful comparison is to gasoline: while pure H2 has a lower ignition energy and higher combustion temperature, the fact that it vaporizes and quickly disperses in air (as opposed to coating surfaces like liquid gasoline) generally renders its accidental combustion less destructive. Nevertheless, a study should be performed of the likely behavior of TALOS' LH2 tank in the event of tank damage, e.g., due to small arms fire.

If a pure-O2 cathode is used, the addition of a second fuel tank (containing LO2) substantially increases the risk of fire or explosion. To the best of our knowledge, no studies have yet been performed on the safety aspects of carrying LO2 in a cryogenic tank near the body. However, LO2 is known to be highly volatile. We therefore propose that a study should be performed to characterize the safety risks of carrying LO2 in the field (and to determine if such risks are acceptable) before proceeding with a pure-O2-cathode fuel cell approach.

Pros/Cons

Air-cathode H2 fuel cells, primarily for automotive applications, have been the subject of significant research and development and have reached a state of fair technology maturity. While the development of a custom fuel cell to meet the needs of TALOS will probably be necessary, similar components are available commercially. Development of a miniaturized vacuum-insulated LH2 tank will also be necessary, along with an integrated thermal management system. In particular, it will be necessary to focus on minimizing the heat transfer to reduce the boil-off of LH2. The resulting power supply system should be capable of meeting TALOS' minimum power and energy targets with both volume and weight to spare. The resulting system would have low noise and minimal vibration, be safely operated indoors or in tight spaces, and present acceptable safety risks. However, it would require active management of TALOS activity to avoid overheating of the fuel cell during peaking power surges.

In order to meet TALOS' stringent power and energy targets, a more advanced technology approach would be required. One option is to move from an air-cathode to a pure-O2-cathode fuel cell. While this may increase power and energy density to the level needed to meet the stringent targets, it also would introduce new technical risks, extend development time, and add a new safety hazard. The safety hazard associated with carrying pure LO2 must be carefully considered before selecting a pure-O2-cathode approach.

Technical Risks

The primary technical risk in development of a TALOS power supply system based on an air-cathode H2 fuel cell is in the development of the LH2 tank. The tank size needed is much smaller than existing LH2 tanks, and it remains to be seen whether it can be sized down to the necessary weight and volume while providing sufficient thermal isolation.

A pure-O2 cathode fuel cell approach carries more risks because such fuel cell technology is less mature. An appropriate LO2 tank must be developed, along with the fuel cell itself. The resulting power supply system may not be capable of meeting the NREL assumed TALOS stringent power and energy targets, or the safety risks associated with carrying pure LO2 may turn out to be unacceptable.

Finally, the thermal system required for a fuel-cell-based approach must reject significant heat to the atmosphere at a (relatively) low temperature, especially during peak power surges. It remains to be determined whether the fuel cell temperature can be kept within the acceptable operating range during peak power surges.

Proposed Development Path

We propose a development path for a TALOS power supply system based on Technical Approach B that would begin with a study into the safety of soldiers wearing cryogenic, atmospheric-pressure LH2 and LO2 fuel tanks in the field. Based on the outcome of this study, the decision would be made whether to pursue air-cathode or pure-O2-cathode H2 fuel cells. In addition, the design of the LH2 and/or LO2 fuel tanks themselves would be informed by the outcomes of the study to maximize safety.

If an air-cathode fuel cell-based power supply for TALOS is to be developed, then we propose that a 2-year design and implementation project be performed (probably by an established fuel cell developer) for the LH2 tank and air-cathode fuel cell. Once the LH2 tank and fuel cell have been developed, a 1-year project would integrate the power system with the TALOS system, and the thermal management system would be designed and integrated. Finally, a prototype of the TALOS with integrated power system would be constructed and tested. Estimated development time is 3 to 4 years.

If a pure-O2-cathode fuel cell-based TALOS power supply is to be developed, then its expected development time would be longer. First, we propose that development of a pure-O2 approach should only be pursued if the safety considerations of soldiers carrying LO2 in the field have been studied and deemed acceptable. In addition to the development of the pure-O2-cathode fuel cell itself (which is not nearly as mature a technology as air-cathode), an even lower-volume LO2 vacuum-insulated tank would also need to be developed. NREL has extensive expertise in advanced fuel cell and hydrogen system development, and one of the most advanced facilities in the world for fuel cell and hydrogen system fabrication and testing. We estimate at least an additional 2 years to develop these parts, extending the development time to at least 5 to 6 years.

Technical Approach C: Advanced Battery

Summary

Our final proposed technical approach is the most promising to meet all of TALOS' technical goals, but is also the highest technical risk and has the longest development time. This approach is based on a suite of advanced battery chemistries with very high energy density. As compared to Technical Approaches A and B, the advanced battery chemistries to be investigated in Technical Approach C have a number of distinct advantages: they produce no significant noise or vibration, require few auxiliary components, have excellent thermal characteristics, and, in general, can be used in a very wide range of challenging environments. However, these battery chemistries have not yet been demonstrated commercially, each carries distinct technical risks, and several have long development times. Therefore, we propose that Technical Approach C should be viewed as the "high risk/high reward" approach, and pursued with the appropriate patience.

The proposed battery chemistries to be investigated are 1) Lithium/Silicon, 2) Lithium/Sulfur, and 3) Single-Use Lithium/Air. Lithium/Silicon (Li/Si) has the shortest potential development time (similar chemistries have recently been commercialized), but is only barely capable of meeting NREL's assumed TALOS minimum power and energy targets and cannot (even in theory) scale to TALOS' stringent targets. Lithium/Sulfur (Li/S) has been demonstrated in lab environments (but not yet commercialized) and can easily meet NREL assumed TALOS minimum power/energy targets (and possibly approach the stringent targets), but is plagued by limited cycle life and strong self-discharge behavior (that is, the battery's stored energy discharges itself even when not in use, limiting its shelf life). Finally, Lithium/Air (Li/Air) has strong theoretical characteristics backed by some experimental results (including extremely high energy density), but has low power density, is vulnerable to contamination from air, may introduce safety concerns, and must deal with volumetric expansion during discharge.

Design

The design of a power system based on any of the proposed battery chemistries is comparatively simple: Just the battery itself, connected directly to TALOS' 48V DC bus with no conversion necessary (see Figure 3). Most batteries have excellent surge capacity (Li/Air possibly being the major exception), and therefore the same device can provide both the base and peak power for TALOS. Most batteries have very efficient chemical-to-electrical energy conversion efficiency, and therefore the heat generated is usually quite minimal. This also means that the only limitation on peaking power duration is the energy it draws from the battery. This simplifies the operator's management of the power system because the operator must only keep track of a single quantity (the remaining energy in the battery). The surge capacity of the battery may be increased either by introduction of a second, higher-power battery chemistry (such as the very mature lead/acid) or an ultracapacitor [9], but this is only necessary to meet the specified TALOS targets (even the stringent targets) in the case of Li/Air.

Figure 3. Energy flow diagram for advanced battery only approach.

Battery Chemistries to Consider

First, we observe that the best energy density of Li-ion batteries (the mature battery technology with highest energy density) is about 0.22 kWhr/kg. To achieve the 30 kWhr necessary to meet TALOS' minimum stored work target, it would be necessary to equip TALOS with a 136 kg (300 lb) battery, far beyond its allowed weight. Therefore, more advanced chemistries are needed.

Lithium/Silicon (Li/Si) is an alternative battery chemistry that has been recently explored quite a bit. A silicon anode has a much higher energy density than the graphite anodes used in conventional Li-ion, and, recently, Silicon-anode batteries have been commercialized (as in the LG G2 SmartPhone). The challenge with these chemistries is that the Silicon in the anode expands to about 400% its original volume during discharge, which requires that the anode be constructed using a nanostructure that allows such expansion [10]. However, Li/Si batteries have been well-demonstrated in laboratory environments to be capable of about 0.8 kWhr/kg (0.53 kWhr/L including expansion) energy density [10], which would yield a 37.5 kg (82.5 lb), 56.6 L battery to achieve the TALOS minimum target 30 kWhr energy. While this is a higher volume than that allowed for TALOS, improved packaging (possibly including expanding packaging with disposal of spent batteries to save volume) may bring this to within range. In addition, Li/Si has been shown to have power density of at least 1 kW/kg, plenty to allow this battery to provide the 6 KW needed for TALOS (minimum) peaking power [10]. However, the 72 kWhr required to meet TALOS' stringent energy target would require a 90 kg (198 lb) battery, which is far too heavy. At present, Li/Si batteries have limited cycle life (~1000 cycles [10]), but otherwise are generally known to be robust and efficient. Given sufficient focus, we estimate that a battery appropriate to meet TALOS minimum power and energy targets could be constructed and integrated within three years, and with only moderate technical risk (mostly associated with the reduction of the volume).

Lithium/Sulfur (Li/S) is a less mature but potentially much more energy dense chemistry, which has not yet been commercialized but may be promising for TALOS. Li/S batteries have been demonstrated in lab environments to have energy density of about 1.2 kWhr/kg (0.8kWhr/L) [11, 12], yielding a 25 kg (55 lb), 37.5 L battery to provide the 30 kWhr for TALOS' minimum power/energy target, or a 60 kg (132 lb), 90 L battery for the 72 kWhr to meet the assumed stringent target. Therefore, Li/S has the potential to allow expansion beyond TALOS' minimum targets while still falling short of its stringent targets (again, volume is the greater issue). However, at present, Li/S batteries suffer a set of problems associated with diffusion of the cathode reaction products, including short cycle life (< 300 cycles), low charging efficiency, and self-discharge [12, 13], which to date have prevented their commercialization. Of these problems, only the self-discharge is damning to TALOS, since cycle life and charging efficiency can be managed with careful maintenance. Self-discharge, however, means that the batteries have a short shelf life, which may prevent their transport and storage for use in the field. Still, if the self-discharge issue can be resolved, Li/S batteries have the potential to boost TALOS power level, exhibit high discharge efficiency, and are non-air-breathing.

Finally, Lithium/Air (Li/Air) batteries are a still very nascent technology but have such extremely high energy densities that they represent one of the few possible ways to meet TALOS' stringent energy target. In an Li/Air battery, oxygen from the air reacts directly with the Lithium anode to produce a very energy dense electricity source. In theory, Li/Air batteries have a potential specific energy of up to 11.6 kWhr/kg [14], and specific energy of up to 3.0 kWhr/kg should be achievable in practice [15]. If the 3.0 kWhr/kg target could be achieved, then a battery to meet NREL's assumed TALOS' stringent 72 kWhr stored work target would weigh only 24 kg (53 lb), and so potentially even higher energy capacities could be achieved.

However, Li/Air is still plagued by a large number of issues. First, generation of a significant amount of power from Li/Air chemistry requires a huge surface area, which at present requires a large volume [14]. While it may be possible to construct a battery using high-surface-area nanostructures, such a method has not yet been demonstrated, even in a lab environment. Second, in order to improve the discharge efficiency of Li/Air, appropriate catalysts are required but have not yet been well established. Li/Air requires the exposure of a sheet of highly-volatile metallic Lithium to the air. Any contaminants in the air, especially water, will permanently damage the battery and prevent recharge. Finally, if an Li/Air battery is physically damaged (such as by small arms fire), then the Lithium sheet may be exposed directly to the air, which could result in a violent and potentially explosive reaction [14].

Because of both the very high potential and risks of Li/Air batteries, we propose that Li/Air batteries be consider as a long-term (>10 years out) option for TALOS or other man-portable power applications. We propose that research projects be performed to resolve some of the basic chemistry issues with Li/Air, particularly the low power density and safety concerns. In addition, because many of the limitations (especially the contamination from air) mostly impact Li/Air rechargeability, we propose that in the near future it should be pursued as a "single-use", non-rechargeable power supply option.

Technical Approach Characteristics

Below we analyze the practical characteristics of a TALOS power supply design based on Technical Approach C, and consider its ability to meet TALOS' tactical utility.

Thermal Management

One of the major advantages of most battery chemistries is their excellent chemical-to-electrical conversion efficiencies, which results in very low heat generation, even at high power levels. For example, both Li/Si and Li/S chemistries often exhibit a chemical-to-electrical efficiency of > = 98%. Even at the assumed TALOS stringent peaking power of 12 kW, this results in a heat rate of only 0.24 kW, a low enough level that it should be possible to reject it to the atmosphere with only a passive heat sink.

Li/Air chemistries may result in lower efficiencies due to the separation of atmospheric oxygen, but the forced convection from the air itself will probably be capable of venting the resulting heat. It is as yet unclear whether such a battery would require any external thermal management.

Pros/Cons

If a power supply system for TALOS can be developed based on one of the above battery chemistries, it would carry a number of distinct advantages. First, for both Li/Si and Li/S, a single battery should be capable of meeting both the base and peak power targets. This has the advantages that the only limitation on TALOS' peaking power duration is the energy it consumes from the battery. Li/Air's lower power density may require that a second battery of a different chemistry (or ultracapacitor) be used to meet the peak power target.

Batteries are silent and produce no vibration or exhaust. They are quite efficient, which results in low heat generation. Both Li/Si and Li/S are non-air-breathing, which means that they can operate successfully underwater or in vacuum (Li/Air requires access to air). Li/Si and Li/S may be recharged and used again, though both suffer from somewhat limited cycle life (Li/Air probably cannot be recharged in the near future). It may even be possible for extra batteries to be carried near TALOS to allow them to be swapped out during mission.

However, the advanced battery chemistries capable of meeting TALOS' high energy density target all have challenges and limitations that have prevented them from being commercialized. Li/Si (the nearest to commercialization) exhibits low cycle life (<1000 cycles) and expansion during discharge, necessitating advanced anode nanostructures. Li/S has very low cycle life (<300 cycles), and significant self-discharge (which limits its shelf life). Li/Air has low power density, potential safety hazards, and suffers from contamination from the air. All of the above require further research work and pose technical risks, and may render the battery unacceptable for use in TALOS.

Proposed Development Path

We propose a series of research and development efforts aimed at alleviating the current limitations in the above battery chemistries and focus on application to TALOS and other man-portable power applications.

First, we propose a research effort to develop a Li/Si battery capable of meeting TALOS' power and energy target within its allowed weight and assumed volume. The proposed research effort would particularly focus on reducing the volume and developing packaging appropriate for TALOS. Since similar chemistries have already been successfully commercialized, we estimate that this effort may be successful within 2-3 years. The resulting Li/Si battery could then be integrated with TALOS and a prototype constructed and evaluated.

In order to render Li/S batteries acceptable for use in TALOS, their shelf life would need to be improved to allow for storage and transport to the theater of operation. We therefore propose a three-year research effort focused on this specific goal. Improvement of the cycle life would be a secondary consideration. If the effort is deemed successful, then we propose a second project to develop an Li/S battery capable of providing as much power as possible (between TALOS base and stringent power/energy targets) within its allowed weight and assumed volume, and to package it appropriately for TALOS. Finally, the resulting Li/S battery could then be integrated with TALOS and a prototype constructed and evaluated. If the effort is successful, we estimate that this prototype could be constructed within 5-8 years.

Finally, we propose longer-term research efforts focused on alleviating the basic chemistry problems encountered in Li/Air batteries to enable their (non-rechargeable) use in to man-portable power applications such as TALOS. These efforts would focus on 1) selection of appropriate catalysts to maximize efficiency, 2) avoiding contamination from the air (especially moisture), 3) improving power density (and specific power) by use of advantaged nanostructures, and 4) packaging for improved safety. Given sufficient investment, it is possible that Li/Air batteries could become viable for TALOS in 10-20 years.

Rejected Approaches and Other Technologies to Consider

Rejected Approaches

In this section, we briefly describe a number of selected technologies or approaches that were considered by the NREL Grand Challenge team and rejected, along with the reasons why those approaches were rejected and cases in which they should be reconsidered.

Nuclear Reactor + Peaking Battery

Some recent research work has considered the possibility of "micro" nuclear reactors that approach the physical size needed for TALOS. However, these reactors are generally targeted at low-power, long duration applications ("watts for years") rather than the "kilowatts for hours" targets faced by TALOS. Therefore, we find that they are not appropriately matched to TALOS' power targets. In addition, nuclear reactors have well-known safety issues and require extensive shielding. Therefore, while future scientific development may render nuclear reactors more appropriate for systems like TALOS, we do not believe such an approach is likely to be promising in the near future (< 10 years).

Peaking Ultracapacitors

The NREL Grand Challenge team considered the use of ultracapacitors in place of the Li-ion peaking battery for Technical Approaches A and B. Ultracapacitors have very high surge rating, but have much lower energy density than Li-ion batteries. Based on commercially available ultracapacitors, we estimate the mass of a 22 Whr, 48 V ultracapacitor to be about 5.3 kg (12 lb), significantly more than the weight of the peaking Li-ion battery selected in Technical Approaches A and B, but with only about a tenth of the stored energy. This results in a complete discharge in about 26 seconds at TALOS' minimum peaking power (as compared to 4 minutes for the peaking battery selected in Technical Approaches A and B).

Therefore, while ultracapacitors could be used in place of the Li-ion peaking battery to meet TALOS' peaking power target, they would result in a much shorter peaking time. They are capable of surging to much more power than a similarly sized Li-ion battery for a much shorter time, but that's not needed to meet TALOS' targets. However, if very high surge power values are needed for short periods of time (a "hundreds of kilowatts for seconds" problem), then a passive-hybrid battery/ultracapacitor solution should be considered.

Energy Harvesting (Renewable Energy) Technologies

Of significant interest with regard to fielded military equipment is the possibility of harvesting energy from the surrounds, such as by photovoltaic (PV) panels, wind turbines, etc. However, while these technologies may be applicable to many kinds of man-portable power systems, we do not believe they are appropriate for the TALOS power supply system. The nature of such "energy harvesting" sources is that they are dispersed over both space and time. Therefore, either a very large area or a long period of time is required to amass significant energy from them, neither of which is available for TALOS.

For example, the peak power from sunlight is about 1 kW/m^2. The best solar collection systems can capture about 20% of the sun's energy, or about 0.2 kW/m^2. Since the maximum surface area presented to the sun by a human body is only 0.5 m^2, this results in an absolute maximum power of about 0.1 kW from the sun on a human body, less than 4% of the power needed for TALOS. Other potential energy harvesting sources result in similar maximum numbers.

Therefore, since TALOS is a "kilowatts for hours" problem, we do not believe that the relatively small contribution from energy-harvesting sources to its required power is worth the additional weight, volume, and other limitations that the inclusion of such technology would entail. However, for other man-portable applications in the "watts for days/weeks" categories (such as those faced by a deployed soldier), then energy harvesting technologies may in fact be very promising.

Rejected Combustion Engines

In addition to the gasoline internal combustion engine included in Technical Approach A, the NREL Grand Challenge team also considered alternative combustion-based power sources, including natural gas turbines, methanol-burning engines, and diesel engines. At a very large scale (megawatts), natural gas turbines have very high efficiency (for combustion engines) and high power-to-weight ratios. However, while natural gas turbines have recently been miniaturized into the sub-kilowatt range (and maintained their high power-to-weight ratios), the resulting engines have very low efficiency, resulting in a very high fuel volume target and significant heat [16, 17]. In addition, this technology is very immature, and its primary advantage over internal combustion engines is its ability to miniaturize to very low powers (Watts or less), which is not required for TALOS. Therefore, we believe that at present, miniature natural gas turbines are not promising for TALOS, though they may be worth considering for other portable-power applications.

Methanol-burning internal combustion engines have excellent power-to-weight ratio (often better than gasoline) and their exhaust is less toxic. However, methanol fuel is not energy dense enough to meet TALOS energy targets. With a lower heating value of only 22.7 MJ/kg and a volume of 0.7910 kg/L, to meet the assumed TALOS energy target of 30 kWhr, about 23.8 kg, 30.1 L of fuel would be required (assuming 20% efficiency), which would increase the weight/volume of the TALOS power supply to unacceptable amounts.

Finally, while diesel is a very common fuel with energy density higher than gasoline's, diesel engines operate at much higher combustion pressures than those used in gasoline engines. As a result, thick cylinder walls are required, and therefore diesel engines have low power-to-weight ratio at the power levels required by TALOS. This results in engines far too heavy to be carried on board the TALOS suit.

Direct Methanol Fuel Cells

The NREL Grand Challenge team considered direct methanol fuel cells as an alternative to H2 fuel cells, because methanol is much easier to store and transport than hydrogen. However, the best power densities of direct methanol fuel cells are on the order of 0.1 kW/L [18], which would result in a fuel cell volume of 60 L to meet even the TALOS' minimum power target (not including any of the other components such as methanol storage). Also, the energy density of methanol is much lower than liquid hydrogen due to need for significant water dilution (usually < 10% methanol by weight [18]). Therefore, direct methanol fuel cells are not a promising technology to achieve the power and energy densities necessary to meet TALOS' targets.

Rejected Hydrogen Storage Mechanisms

In Technical Approach B, we chose cryogenic liquid hydrogen (LH2) storage in a vacuum-insulated tank as the most viable approach to the storage of the hydrogen fuel for the fuel cell. There are several other possible approaches to hydrogen storage, including hydrogen reformation from liquid fuels, solid (metal-hydride) storage, and pressurized gaseous hydrogen storage, but we rejected each of these as not promising for TALOS.

Hydrogen for fuel cells can be reformed from liquid hydrocarbon fuels such as methanol or natural gas. However, this process produces carbon monoxide (CO), carbon dioxide (CO2), and other non-hydrogen gases. These gases are difficult to separate from the hydrogen fuel, and if they are introduced to the (PEM) fuel cell poison the platinum catalyst and significantly reduce fuel cell efficiency and increase needed fuel cell size and needed fuel. CO and/or CO2 can be separated from H2, but the process is energy intensive, thereby consuming much of the power produced by the fuel cell. In addition, reformation of hydrocarbon fuels to hydrogen requires an extensive chemical processor, which adds significant weight/cost/volume/complexity. Finally, liquid hydrocarbon fuels are less energy dense than pure hydrogen, which will likely render them incapable of meeting TALOS' energy storage target within allowed volume. Because of all the above, we believe that direct hydrogen storage is the better approach for TALOS.

Hydrogen can be stored in solid metal hydrides by compressing hydrogen gas onto certain metals at high temperature, which allows storage of hydrogen at lower volumes and pressures than gaseous storage alone. However, the highest H2 mass ratio (mass of hydrogen over mass of the metal) available for metal hydrides (Mg2HiH4) is about 3.59 % [19]. In order to store the 1.5 kg of H2 needed for TALOS' minimum stored work target, the fuel storage alone would weigh 41.8 kg (91.9 lb), nearly the entire allocated weight for the power supply (not including the fuel cell or battery). In addition, metal hydride fuel storage must usually operate at high temperatures (>= 200 C). Finally, extraction of the hydrogen gas from metal hydrides is slow, and unlikely to be able to meet the high ramp rates required for TALOS. Therefore, we do not think metal hydrides are likely to be a promising hydrogen storage mechanism for TALOS in the near future.

Finally, compressed gaseous H2 (at near ambient temperature) is used for most automotive fuel-cell applications. These tanks store gaseous hydrogen at very high pressures (700 bar has recently become the standard), and therefore are generally quite heavy. A steel wall pressure tank (which has the highest safety margins) usually has an H2 weight ratio of about 4% [19], which would require a tank weighing 37.5 kg (82.5 lb) to hold the 1.5 kg of H2 required for TALOS minimum targets, which is too heavy in combination with the fuel cell and battery. Advanced carbon fiber pressure tanks provide an H2 weight ratio of about 6% [19], allowing a 25 kg (55 lb) tank to hold the 1.5 kg H2 needed for TALOS' minimum target, but still too heavy (60 kg, 132 lb) for the stringent target's required 3.6 kg H2. In addition, even at 600 bar (the maximum allowed pressure in such tanks) the stored gaseous H2 has even more volume than cryogenic LH2 (28.2 kg/L [19], yielding a tank from 42.2/101 L for the assumed minimum/stringent energy targets). Therefore, the volume of gaseous H2 is too high to meet stringent energy targets, and even minimum targets are difficult to meet within volume.

Wireless Power Transfer

In order to avoid the necessity of carrying the entire power supply system needed to meet TALOS targets on board, it might be possible to wirelessly transfer power from a remote power station to the suit itself. However, it is quite difficult to transfer the amount of power needed by TALOS (3 – 12 kW) wirelessly over any significant distance. In addition, wireless power transfer requires an open and/or carefully configured environment in order to ensure that TALOS maintains continuous line-of-sight to a nearby wireless power transmitter. However, requiring TALOS to be "tethered" to a wireless power station would severely limit its ability to operate in the uncontrolled, often enclosed combat environments for which it is primarily intended. If a man-portable power application was to work in a more controlled environment (e.g., aboard ship, on base, etc.), then wireless power transfer may be more applicable.

Other Technologies to Consider

Higher Voltage (> 48 V) DC Bus

A higher DC bus voltage (greater than 48 V) would result in fewer losses from electric power transfer across TALOS. In addition, to provide TALOS' minimum peak target of 6 kW electrical to the TALOS actuators at 48V would require 125A continuous DC current, which would require large (1/0 AWG) cabling that may limit TALOS' movement. However, going to a much higher voltage (>100 V) would add another safety hazard, since voltages greater than 100 V DC are considered hazardous for use where a human body may come into contact [20]. If TALOS is damaged and electrical conductors are exposed, high DC voltages may injure or muscle-lock the operator and/or anyone who comes in contact with the suit. In addition, heat due to conductive losses in TALOS should be fairly small (because electrical distances are short). Therefore, we propose continued use of the 48 V DC bus voltage for TALOS' minimum power level (3 kW continuous), because it eliminates the shock/muscle-lock risk at only moderate cost in energy losses. Slightly higher voltages not more than 100 V DC may be considered for higher power levels.

Modular Power Components

We anticipate that some missions may require or benefit from supplemental TALOS capabilities. TALOS should be designed to modularly accept supplemental equipment but should NOT be required to power them. If supplemental equipment modules require power, they should be required to either harvest it (e.g., powered aerial drop equipment should capture energy from air drag) or carry their own internal power system.

Summary of Technical Roadmap and Conclusions

Below we summarize our proposed technical roadmap based on the above designs, as well as our conclusions on man-portable power applications in general.

Summary of Technical Roadmap

Figure 4 shows the timeline of our proposed technical roadmap for TALOS power supply development, including each of the proposed efforts for Technical Approaches A, B, and C. We summarize the proposed technical roadmap and present our conclusions below.

In order to deploy a TALOS power system solution within 2 years, we believe Technical Approach A (Combustion Engine + Peaking Battery) is the only viable option. However, this approach will severely limit TALOS' flexibility and tactical usefulness because the basic physics of combustion engines render them incapable of meeting many of TALOS' targets. In particular, a TALOS based on combustion engine technology is likely to be plagued by noise, vibration, and thermal issues, thereby impacting operator comfort. It will not be safe to operate indoors or in tight spaces, and cannot operate underwater. Its exhaust is likely to present a health issue to either its operator or other nearby personnel, and its gasoline tank may present risk of fire. Finally, the limited energy density of combustion fuels and low efficiency of combustion engines render it unlikely that any combustion-based power supply system will be capable of meeting TALOS' stringent power and energy targets. However, development of a TALOS prototype based on Technical Approach A may be useful as a "baseline" for model development, prototyping of other TALOS subsystems, and comparison for other technical approaches.

Because TALOS is such a new type of system, and because thermal and power management is likely to be so important, we also propose development of a software thermal and energy modeling system for TALOS to assist in development, testing, and deployment. This software model, based on a selected set of missions for TALOS and the associated energy targets, could be developed in parallel with Technical Approach A and validated by comparison to a TALOS prototype based on Technical Approach A. In addition, construction of such a prototype would allow development and testing of other TALOS subsystems while the basic science is being done to enable more capable power supply technologies.

Both Technical Approach B (H2 Fuel Cell + Peaking Battery) and Technical Approach C (Advanced Battery) require longer development time and more technical risk, but are much more promising in the long term. Technical Approach C (Advanced Battery) is the most promising to meet all targets in the long term, but has long development time, high technical risk, and may turn out not to be viable. We therefore propose parallel pursuit of both Technical Approaches B and C (Fuel Cell + Peaking Battery and Advanced Battery Only) to determine which is more viable.

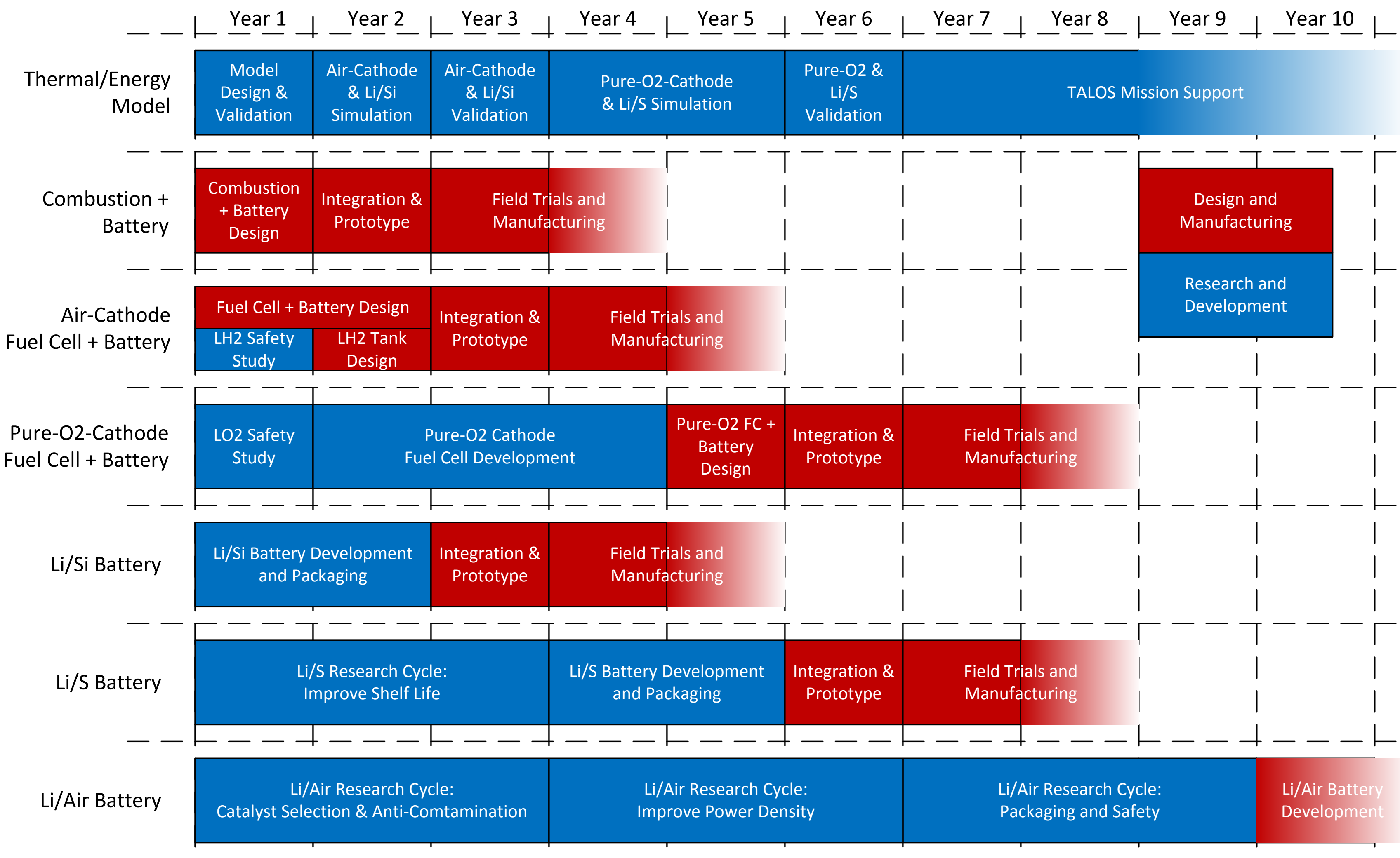

Figure 4. Timeline for proposed technical roadmap for TALOS power supply development.

Because (to the knowledge of the Grand Challenge team) no studies have yet been performed on the safety and health concerns of military personnel carrying LH2 and/or LO2 in the field, we propose such a study to assess the safety risks and determine whether they are acceptable. If the proposed study deems the risks acceptable, then using the previously developed TALOS thermal and energy model, a passive-hybrid LH2 fuel cell + battery power supply system could be designed based on the assumed TALOS power/energy targets, along with the appropriate thermal management system. This design effort would include development of a vacuum-insulated LH2 tank to meet the TALOS energy target. Finally, the resulting hybrid LH2 fuel cell + battery power supply system could be integrated with a new TALOS prototype suit and validated by field trials.

In parallel, we propose a three-year research effort to address the self-discharge (and, to a lesser extent, cycle-life) limitations of current-generation Lithium-Sulfur battery chemistries. The focus of this effort would be to develop a shelf-stable Lithium-Sulfur battery appropriate to meet TALOS power and energy targets. Next, the resulting batteries could then be appropriately packaged for TALOS and integrated (again, via the thermal and energy TALOS model) with an appropriate thermal management system. Finally, a third TALOS prototype based on Lithium-Sulfur battery technology could then be developed and compared via field trials to both the original (combustion-based) and fuel-cell-based prototypes. It may then be determined whether either one or both of the fuel-cell- and battery-based approaches remain promising and which, if either, is appropriate for TALOS implementation.

If the fuel-cell-based approach remains promising, then we propose that a pure-O2 cathode fuel cell technology for the TALOS power supply should be considered. This approach introduces the additional risk of LO2 combustion, but seems at present to be the most promising path to reach the stringent TALOS power and energy targets. If the results of the proposed LH2/LO2 safety study demonstrate that the risk of carrying LO2 in the field is acceptable, then we propose a 3-year research effort to develop man-portable, pure-O2 cathode fuel cells, along with appropriate LH2 and LO2 tanks. A TALOS power supply system based on pure-O2-cathode fuel cell technology could then be developed and integrated, resulting in a final fuel-cell-based prototype, which may be capable of nearing TALOS' stringent power and energy targets while generating acceptable heat with minimal noise, vibration, and exhaust.

Finally, while it is unlikely to result in a deployable power supply system for TALOS in the next decade, we propose that Li/Air-based battery technologies be pursued through research efforts to develop batteries appropriate for TALOS or similar man-portable power applications due to their very high energy density. Such research efforts would focus first on selecting appropriate catalysts to maximize efficiency and power density while reducing the battery's vulnerability to contamination from the air, then on improving the battery's power density to a level capable of meeting TALOS' targets, and finally on appropriately packaging such an Li/Air battery to improve safety for man-portable power applications. If such research efforts are successful, then it is possible that an Li/Air battery capable of meeting TALOS' targets and beyond could be developed within 10 to 20 years.

If the proposed technical roadmap is successful, the result will be not only the development of a power system capable of powering the TALOS suit, but also new technical approaches capable of powering other man-portable or mobile applications. If other man-portable power applications are to be considered that have different power level and timing needs from TALOS (e.g., watts for days/weeks instead of kilowatts for hours), or which operate in more controlled environments (such as onboard ship or on base), then some of the rejected approaches (such as energy harvesting or wireless power transfer) should be reconsidered for those applications.

Conclusions

In conclusion, while it is possible to meet TALOS' power and energy targets using existing technology (Technical Approach A), this approach has very limited tactical applications and is a dead-end for meeting the stringent goals. Both H2 fuel-cells (Technical Approach B) and advanced energy chemistries (Technical Approach C) have potential, but it is impossible at this point to determine which is more promising in the long run. We therefore propose parallel pursuit of both approaches, along with periodic comparison to each other.

We think it is also important to recognize that man-portable power is a very new application, which has distinct characteristics from most existing power system applications and therefore requires different technology approaches. Conventional combustion-based technologies create both thermal, comfort, and environmental issues that are more of a problem for man-portable power than for vehicle applications. Fuel cells are promising, but will still present some thermal issues and fuel storage is challenging and presents possible safety issues. Advanced batteries seem the most promising in the long run, but fundamental chemistry problems present a technical risk. A major goal should be to minimize the use of power electronics, which are heavy and sensitive to shock/vibration.

In addition, any technology approach for man-portable power is very application specific. For example, TALOS is a "kilowatts for hours" problem and, therefore, meeting the its base and peaking power targets within the weight and volume targets requires both high power density and high energy density, which are very difficult to obtain simultaneously. Either a "watts for days/weeks" problem or a "100's of kilowatts for seconds" problem would likely result in a very different set of technology approaches and, therefore, many of the technologies rejected for TALOS may make sense in other man-portable power applications.

Finally, development of the technologies necessary for TALOS will not only have application to other man-portable power application, but will also benefit other kinds of applications and enable capabilities that are not present today. For example, development of pure-O2 fuel cells may benefit automotive applications, and development of new battery chemistries may enable new kinds of mobile devices that require more power than is available in today's smartphones. Investment in these technologies, while expensive in the short term, will pay large dividends in benefits for not only the military but all of civilian society in the future.

References

[1] S. Mekhilef, R. Saidur, and A. Safari, "Comparative study of different fuel cell technologies," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 981-989, 1// 2012.

[2] T. Abdel-Baset, T. Benjamin, R. Borup, K. E. Martin, N. Garland, S. Hirano*, et al.*, "Fuel Cell Technical Team Roadmap," USDRIVEJune 2013.

[3] B. M. Information, "BWM Hydrogen 7," BWM Media InformationNovember 2006.

[4] J. Bernard, M. Hofer, U. Hannesen, A. Toth, A. Tsukada, F. N. Büchi*, et al.*, "Fuel cell/battery passive hybrid power source for electric powertrains," *Journal of Power Sources,* vol. 196, pp. 5867-5872, 7/15/ 2011.

[5] C. Chen, Y. Kang, Z. Huo, Z. Zhu, W. Huang, H. L. Xin*, et al.*, "Highly crystalline multimetallic nanoframes with three-dimensional electrocatalytic surfaces," *Science,* vol. 343, pp. 1339-1343, 2014.

[6] L. E. Snyder, "A feasibility study of internal evaporative cooling for proton exchange membrane fuel cells," Texas A&M University, 2006.

[7] S. S. Kocha, "Polymer electrolyte membrane (PEM) fuel cells, automotive applications," in *Fuel Cells*, ed: Springer, 2013, pp. 473-518.

[8] K. Pehr, "Aspects of safety and acceptance of LH2 tank systems in passenger cars," *International Journal of Hydrogen Energy,* vol. 21, pp. 387-395, 5// 1996.

[9] A. Kuperman and I. Aharon, "Battery–ultracapacitor hybrids for pulsed current loads: A review," *Renewable and Sustainable Energy Reviews,* vol. 15, pp. 981-992, 2// 2011.

[10] H. Wu, G. Yu, L. Pan, N. Liu, M. T. McDowell, Z. Bao*, et al.*, "Stable Li-ion battery anodes by in-situ polymerization of conducting hydrogel to conformally coat silicon nanoparticles," *Nature communications,* vol. 4, 2013.

[11] H. Wang, Y. Yang, Y. Liang, J. T. Robinson, Y. Li, A. Jackson*, et al.*, "Graphene-Wrapped Sulfur Particles as a Rechargeable Lithium–Sulfur Battery Cathode Material with High Capacity and Cycling Stability," *Nano Letters,* vol. 11, pp. 2644-2647, 2011/07/13 2011.

[12] S. S. Zhang, "Liquid electrolyte lithium/sulfur battery: Fundamental chemistry, problems, and solutions," *Journal of Power Sources,* vol. 231, pp. 153-162, 6/1/ 2013.

[13] A. Manthiram, Y. Fu, S.-H. Chung, C. Zu, and Y.-S. Su, "Rechargeable Lithium–Sulfur Batteries," *Chemical Reviews,* vol. 114, pp. 11751-11787, 2014/12/10 2014.

[14] G. Girishkumar, B. McCloskey, A. C. Luntz, S. Swanson, and W. Wilcke, "Lithium−Air Battery: Promise and Challenges," *The Journal of Physical Chemistry Letters,* vol. 1, pp. 2193-2203, 2010/07/15 2010.

[15] B. Kumar, J. Kumar, R. Leese, J. P. Fellner, S. J. Rodrigues, and K. Abraham, "A solid-state, rechargeable, long cycle life lithium–air battery," *Journal of The Electrochemical Society,* vol. 157, pp. A50-A54, 2010.

[16] J. Peirs, D. Reynaerts, and F. Verplaetsen, "Development of an axial microturbine for a portable gas turbine generator," *Journal of Micromechanics and Microengineering,* vol. 13, p. S190, 2003.

[17] H. Abarbanel, L. Bildsten, P. Dimotakis, F. Dyson, D. M. Eardley, S. M. Flatté*, et al.*, "Portable Energy for the Dismounted Soldier," *JSR,* vol. 2, p. 135, 2003.

[18] X. Li and A. Faghri, "Review and advances of direct methanol fuel cells (DMFCs) part I: Design, fabrication, and testing with high concentration methanol solutions," *Journal of Power Sources,* vol. 226, pp. 223-240, 3/15/ 2013.

[19] L. Schlapbach and A. Zuttel, "Hydrogen-storage materials for mobile applications," *Nature,* vol. 414, pp. 353-358, 11/15/print 2001.
[20] U.S. Department of Energy, "DoE Handbook - Electrical Safety," ed. Washington, D.C.: U.S. Department of Energy, 2013, pp. D-4,D-5.