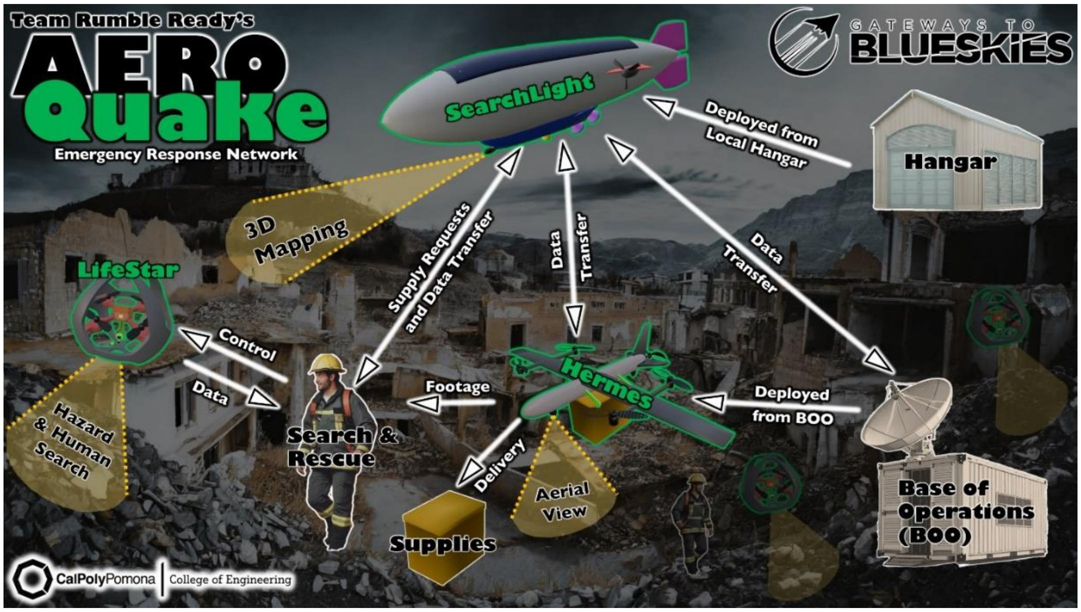
California State Polytechnic University, Pomona

College of Engineering, Aerospace Engineering Department



Aero-Quake Emergency Response Network

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I. Table of Contents

II. Proposal Compliance Matrix

Req ID	Requirement	Compliance?	Section(s)	Page(s)
SA1	Select one type of natural disaster and one phase of disaster management to focus on (preparation, response, or recovery)	Yes	1.0	1
SA2	For the selected type of natural disaster, assess its current impacts, the people involved in the disasters' management, and aviation-related operations and technology currently utilized.	Yes	1.1,1.3	1
SA3	Clear CONOPs description, demonstrating thorough and proper research, practical applications, and realistic assumptions.	Yes	1.4	2
SA4	Team defined use case/opportunity for impact/aviation related systems identified to address the opportunity.	Yes	1.2	1
SA5	Consider the operational context surrounding the system, i.e., those impacted by the proposed technology, decisions made from information collected (and who makes the decision), what part of the process is the technology improving, etc.	Yes	1.4, 2.7	1,6
IA1	Clear depiction of systems integration approach, including an understanding of integration factors.	Yes	3.0-3.5	7-9
IA2	Include trades on: simplicity, cost/ROI, support system requirements, connectivity restraints, limitations from environmental conditions, expected improvements over existing practices, interoperability with existing people, operations, technologies, and solutions.	Yes	2.0-2.8	4-7
TB1	Chart a path to deployment: Conduct analysis of the pathway and timeline to implementation for the system(s) by 2035, including, but not limited to: technology readiness levels, training, customer/stakeholder operational integration, and opportunity/barrier analysis (technology/development, policy and regulations, risks, etc.).	Yes	3.0-3.5	7-10
KF1	Final paper makes a compelling case for concept implementation.	Yes	4.0	10
AS1	Highlight clear changes made between proposal and final technical paper.	Yes	5.0	11
L1	Proposal is 8-10 pages excluding Cover Page, Abstract, Table of Contents, and Appendices.	Yes		
L2	Reads as a stand-alone document.	Yes		
L3	Single spaced and single column.	Yes		

L4	Standard 1" margins all around.	Yes		
L5	Uses a common font (i.e., Times, Times New Roman, Helvetica, or Arial for text, Symbol for mathematical symbols and Greek letters)	Yes		
L6	Front size should be either 11 or 12 put (including in all tables, charts, and graphs).	Yes		
L7	Monday May 13, 2024 9 pm PST	Yes		
IG1	Creative use of color, graphics, images, photos	Yes		
IG2	Well laid out components that clearly overview the opportunity space/team-determined use case in the selected in the selected natural disaster and management phase	Yes		
IG3	Covers current solution, proposed solution, and projected improvements	Yes		
IG4	Conceptualized approach to deployment (timeline, opportunity, and challenges), including references	Yes		
IG5	The infographic is standalone (including acronyms) and simple to understand (no heavy technical jargon)	Yes		
IG6	Representative of the findings of the final report	Yes		
IG7	Monday May 13, 2024, 9 pm PST	Yes		
IG8	300 ppi	Yes		
IG9	100 mb size maximum	Yes		
IG10	Using "California State Polytechnic University, Pomona - 2024 Blue Skies Infographic" as the name of the file.	Yes		
IG11	Small team identifier in bottom left hand (ie: university name, team name)	Yes		
IG12	No outside links are permitted except for references	Yes		
IG13	Must be uploaded as pdf	Yes		
IG14	Horizontal	Yes		
IG15	9600 x 7200 pixels (48" x 36") size	Yes		
IG16	Infographic should have a title	Yes		
O1	High resolution graphic of concept with minimum dpi of 300	Yes		
O2	2-3 sentence synopsis of 600 characters	Yes		

III. List of Figures

IV. List of Tables

V. List of Acronyms

ACDM	African Center for Disaster Management
ADRC	Asian Disaster Reduction Center
AI	Artificial Intelligence
AQERN	Aero-Quake Emergency Response Network
BOO	Base of Operations
Comms	Communication System
CONOPs	Concept of Operations
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
LiDAR	Light Detection and Ranging
ML	Machine Learning
NATO	North Atlantic Treaty Organization
NLE	National Level Exercise
SAR	Search and Rescue
TLM	The Last Mile
TRL	Technology Readiness Level
UAS	Uncrewed Aerial System
UHF	Ultra High-Frequency (radio)
UKISAR	United Kingdom International Search and Rescue
USAR	Urban Search and Rescue
VHF	Very High Frequency (radio)

0. Abstract/Summary

This proposal responds to NASA's 2024 Gateways to Blue Skies: Advancing Aviation for Natural Disasters Competition by identifying a new emergency response aviation architecture for earthquakes that can be implemented by 2035. Three major problems in earthquake disaster response are lack of communication, hinderance of supply delivery due to destroyed road infrastructure, and locating victims in the critical 72-hour survival window. To address these challenges, Team Rumble Ready proposes the Aero-Quake Emergency Response Network (AQERN): a scalable architecture for earthquake disaster response. The architecture is comprised of three aviation elements — Searchlight, Hermes, and LifeStar — which address communication with responders, supply delivery, and mobile search-and-rescue (SAR) operations respectively as seen in Figure 0.1 below. Searchlight, a lighter-than-air vehicle, enables wireless communication between different response teams and bases of operations (BOO) about points of interest and their needs. Hermes, a mixed- fixed wing drone, can respond to those needs by delivering emergency supplies while using aerial imaging with artificial intelligence (AI) for operational independence. LifeStar is a small portable drone encompassed by a protective spherical cage used to identify survivors and hazards in environments too risky for rescuers.

Since the original proposal, further research, trade studies, and feasibility assessments on the integration of this architecture and its improvements to current response procedures have been performed. Operations, customer integration, cost, and sizing of the systems have been refined. Feasibility studies on individual system duration, risk mitigations due to environmental conditions and technology failure were done as well. AQERN considers the concerns of search and rescue teams by assessing current procurement procedures and ensuring AQERN involves minimal change in current response procedures. Furthermore, AQERN is compatible with current technologies while remaining modular for integration of future technology. Investing in this architecture would be about 0.9% of the world's annual disaster response budget while saving 160,000 lives in the first 10 years. By considering the integration of both existing and developing technologies into innovative applications for earthquake disaster response, AQERN enables a planned operational implementation into current emergency response procedures that is viable by the year 2035.

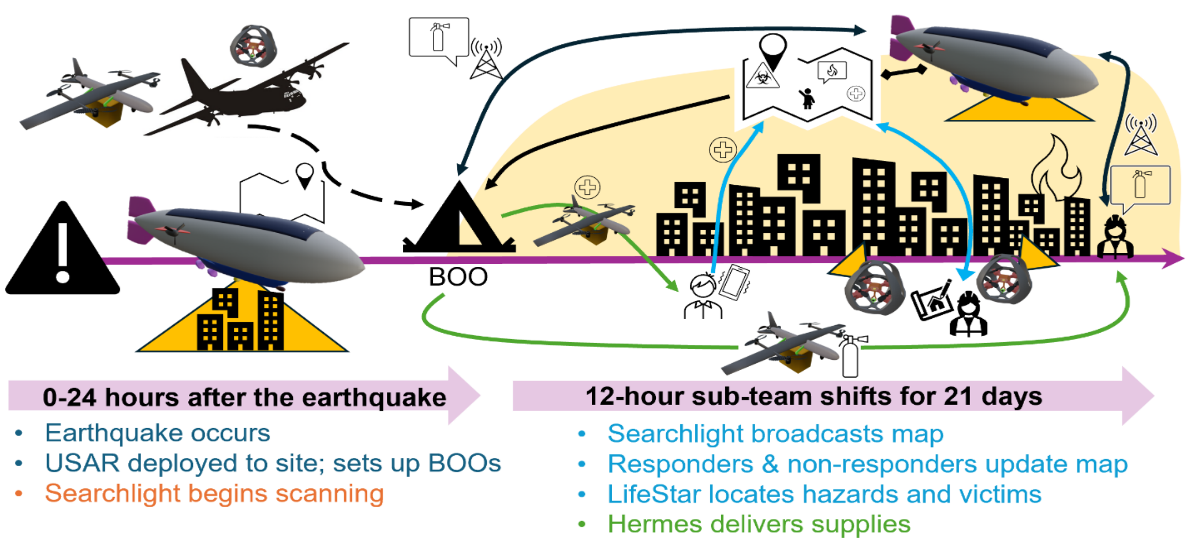


Figure 0.1: Aero-Quake Procedure

1.0 Situational Assessment and Concept of Operations (CONOPs) Description

Earthquakes cause major damage to infrastructure and communications, hindering search and rescue operations. The Aero-Quake Emergency Response Network, a system of systems, uses three interoperable systems to solve responder communication infrastructure, supply logistics, and victim and hazard's location to aid victims in the first critical 72 hours.

1.1 Earthquake Background

The earth has seven major tectonic plates and countless fault lines that may slip at any time and cause an earthquake without warning [1]. Although earthquakes make up only about 8% of all natural disasters worldwide, they have caused 58% of all natural disaster related deaths in the 21st century [2][3]. This destructive nature is a building issue as over 1.5 billion people live in earthquake prone areas seen in black and gray in Appendix A and the population in these areas is growing faster than the global average [4].

1.2 Use Case

Response challenges identified from the devastating 2023 Turkey-Syria earthquakes include delayed delivery of essential aid and supplies, disrupted communications, and locating victims under rubble [5,6,7]. Despite responders pulling over 8,000 survivors from the rubble, the deadly quake claimed the lives of over 53,000 people [8,9]. Since many of these deaths are from conditions like hypothermia, fires, injuries, tsunami backwash, chemical spills, and diseases, the goal is to increase the speed of earthquake response [3]. Furthermore, although some victims were rescued alive after being trapped for 10 days, the typical survival rate for those trapped longer than three days drops to between 5-10% [10,11].

To increase the number of survivors pulled alive from rubble and provide them necessary aid in the first 72 hours, an aviation-based architecture is needed that can 1) establish a strong communication network, 2) rapidly disperse critical supplies, and 3) collect and distribute data to aid victims faster.

1.3 Understanding General Emergency Response Procedure

The United States organization that coordinates disaster response is the Federal Emergency Management Agency (FEMA). It oversees 28 task forces comprised of 70 specialists. These specialists are certified for urban search and rescue (USAR) and may have expertise in fields such as rescue, logistics, communications, medical, structures, and heavy equipment [12]. In the event of a disaster, FEMA will dispatch an appropriate number of task forces to the affected area. Other search and rescue teams, deployed by local and state departments, nonprofit organizations, and the military often also join operations.

On-site, these teams first establish a BOO to conduct business for up to 21 days under the assumptions listed in Table 1.3.1. As of 2024, USAR teams use a wide variety of technologies such as thermal imaging, satellite communication, aerial mapping, microwave heartbeat finders, and drones [13,14]. However, uncrewed aerial system (UAS) use is infrequent as there are no UASs that are federally approved for use in USAR, and no UAS is provided as a federal resource as they do not appear on the FEMA Approved Equipment Cache List. However, helicopters or aircraft sourced from local agencies are often used for initial damage assessment of the area.

Table 1.3.1: Assumptions derived from current emergency response procedures.

Assumptions	
• No power, communication towers, internet.	• BOO located outside of the disaster area.
• No aerial transportation of fuel.	• Airspace primarily commanded by military.
• Fuel can be sourced onsite.	• Transported supplies must fit in C-130Js.
• Rescuers work in 12 hour shifts.	• Heavy machinery can be sourced onsite.
• Individual response task forces must be self-sufficient for a 21-day deployment.	• Emergency personnel can fly with Certificate of Waiver/Authorization.
• Ultrahigh frequency (UHF) radio is used within individual response teams.	• BOO and sub-teams on missions are too far to communicate with each other via radio.

1.4 Concept of Operations (CONOPs)

The Concept of Operations (CONOPS) for Aero-Quake (Figure 1.4.1) uses three elements to solve a multi-

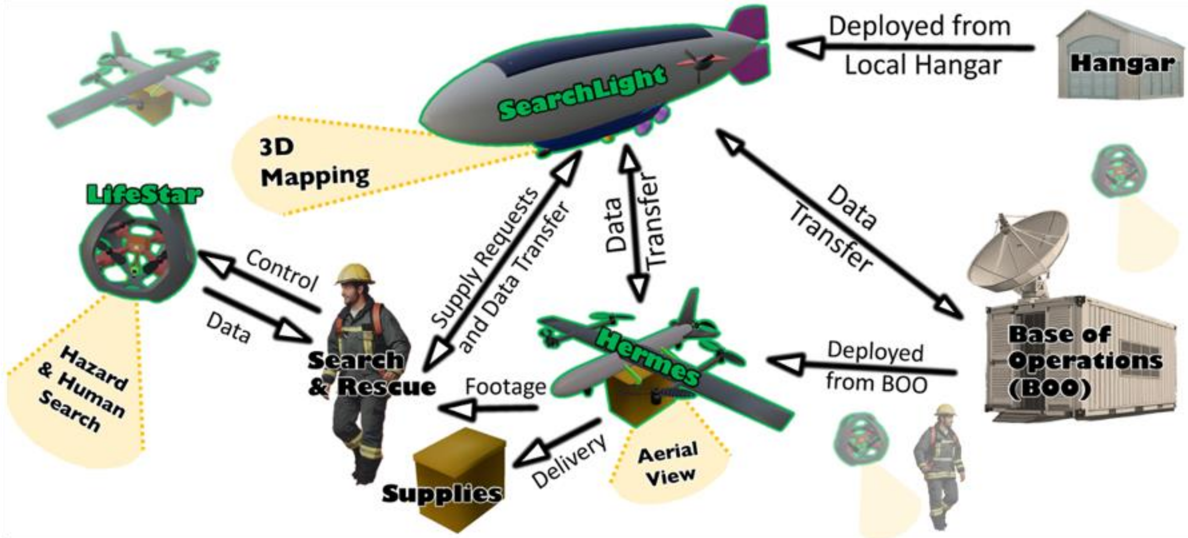


Figure 1.4.1: The AQERN CONOPs image includes Searchlight, Hermes, and LifeStar sharing data.

level problem. Searchlight surveys the site generating a map which is then hosted on a server for responders to mark and give information about points such as collapsed hospitals, fires, victim locations, etc. Hermes, stationed at BOOs and supply stations, readily provides autonomous delivery of critical supplies to rescuers based on requests transmitted through searchlight. At the site, responders use LifeStar as a tool to search for hazards and victims in spaces that are risky for rescuers. Rescuers can upload information/make requests to the BOO from Searchlight as needed.

1.5 Aero-Quake Emergency Response Network (AQERN) System of Systems

AQERN's is made up of the three systems and technologies seen in Table 1.5.1. Since the first proposal, several trade studies (summarized in Table 1.5.2 and Appendix B) including technologies and sizing were performed for each system in AQERN.

Table 1.5.1: Specification Table for Searchlight, Hermes, and LifeStar.

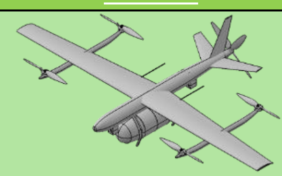
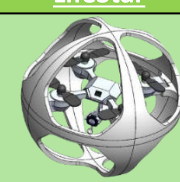
Parameter	Searchlight	Hermes	LifeStar
Isometric View			
L x W x H	230' x 36' x 34'	5.8' x 10' x 1.6'	⌀1.6'
Weight	33,000 lbs., 65 lbs. payload	75 + 25 lbs. payload	6.2 lbs.
Duration	3 days	8 hr.	45 min.
Technologies	Wi-Fi, VHF/UHF radio repeater, Satellite Connection, Solid State Batteries (SSBs) Thin Film Solar Cells	AI Full Autonomy, Quiet Propellers, VTOL, LiDAR SSBs	Camera, Speaker, Microphone, Gas detection, LED Light, SSBs
Benefit to Operations	Initial survey Communication Relay	Supply Delivery Detailed survey	Hazards & Victim Location
Unit Flyaway Cost	$18,298,000	$11,912	$1,508

Table 1.5.2: Summary of System Design Trade studies

Design point	Trade study	Results
Searchlight		
Propulsion	Electric vs. Diesel	Electric is unrealistic with a battery estimate of 107,000 lbs.
Communication Technology	5G vs. Wi-Fi vs. UHF/VHF	A combination of Wi-Fi, UHF and VHF maximizes universal usage and reduces antenna number from 25 to 12
Endurance	Endurance vs. cost	Each day of endurance past 3 costs ~$50 million/day. This is a great cost for limited benefit.
Hermes		
Pusher motor	Electric vs. Diesel	Using diesel increases weight by 6lbs. and endurance by 2h.
Payload size	Payload vs UAS size	25lb. encompasses most items used in the first 27 hours. Additional payload capacity increases system weight by 10 lbs.
Propeller type	Conventional vs. quiet propeller	Quiet toroidal propellers were selected for 10-15dBA noise reduction with 2-4% efficiency increase
LifeStar		
Gas detection	Detected gasses vs. cost	Detecting CO2, CO and hydrocarbons with a module for more specific sensors added <1oz. of weight
Propeller type	Conventional vs quiet	Use of toroidal propellers increased endurance by 2 min for no additional weight and minimized communication interference
Camera type	Camera type vs. weight	Introduction of a thermal camera improves LifeStar's night vision and dust penetration abilities while adding only 0.7 oz

1.6 Analysis of Alternatives

In Table 1.6.1, current USAR methods of handling communications, supplies, and rescues are summarized along with current alternatives and the proposed AQERN solution. Some notable alternatives are portable cell towers and robotics. Portable cell towers were used when responding to the Turkey-Syria earthquake but were targeted at contacting family, slow to launch, and had limited range [14]. Ground based robotics have seen limited use in disaster response but are not widespread due to issues adapting to all terrain.

Table 1.6.1: Analysis of Alternatives to AQERN

Technology	Current Solution	Current Alternatives	AQERN's Projected Solution
Communications	• UHF /VHF radios • Satellite phones	• Portable cell towers	• Aerial imaging & communication hub
Supply Support	• Trucks/Motorcycles • People on ground	• Helicopter • Pilot drones supply	• Short turnaround time for aid delivery on request
Rubble Searching	• Heavy equipment • Sonar/sound mics • Specialized rescuers	• Firefighting, rescue, and live streaming robots	• Hazard/victim locating ball drone unobstructed by ground conditions
Aerial Support	• Helicopters/planes with cameras	• VTOL drones	• Lighter-than-air vehicle • Mixed-wing drone

2.0 Implementation Analysis

AQERN emphasizes simplicity in operation, maintenance, and deployment to enable a rapid disaster response and integration in existing FEMA response procedures [Section 2.2, [15]]. The use of line replaceable parts such as batteries and propellers for efficient deployment and repair, stationing Searchlight near locations prone to earthquakes, and incorporating intuitive operating procedures such as phone app access and standard quadcopter controls ensures that AQERN will be swiftly responsive and integrated into emergency protocols.

2.1 Overall Analysis of Integration Approach

Aero-Quake operates as an addition to current emergency response procedures, as shown in Figure 2.1.1.

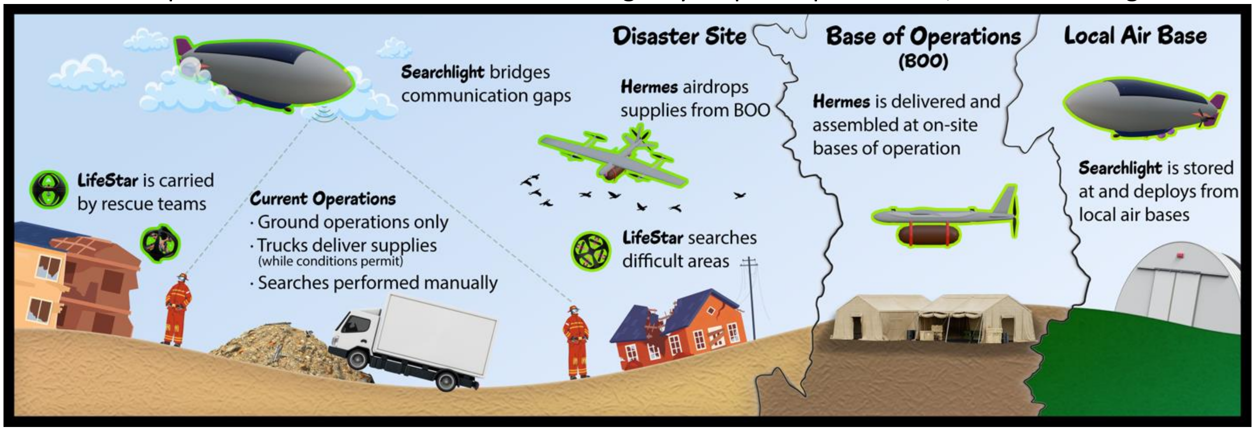


Figure 2.1.1: Current + AQERN Operation

2.2 Simplicity

Aero-Quake maintains simplicity within the maintenance, interface, deployment, and technologies used. Searchlight will be stationed within U.S. global military bases to reduce international integration hurdles. Each of the technologies will be implemented with some existing technologies and modular parts so that development and repair process is quick and inexpensive. Requests for supplies from Hermes will be made through a mobile app to maximize ease of access for all responders. LifeStar's low weight and cage enables portability so it can easily be clipped bag straps for transportation. Each of the systems can be integrated into the current FEMA response procedure without altering operations and can perform independently of the other elements. Fitting into FEMA guidelines allows implementation into international procedures as many foreign entities work alongside FEMA or follow their guidelines.

2.3 Cost and Return in Investment

Materializing Aero-Quake involves development and production costs for the three vehicles. The cost, as presented in Table 2.3.1, was calculated using the Rand Corporation costing method which considers the quantities to be produced, max flight speeds, and the weights of the vehicles [16]. These costs add up to a total investment of $1.3 billion ($2024). The net present value, using a 12% hurdle rate, will break-even after 5 years and reach a 15% profit margin after 8 years, as seen below in Figure 2.3.1. At the end of a 10-year production period, the net present value is expected to reach $300 million ($2024).

Table 2.3.1: Cost Table

	Searchlight	Hermes	LifeStar
Production Units	50	4,000	10,000
Airframe Engineering	$180,620,000	$1,926,000	$344,910
Development Support	$18,243,000	$224,750	$34,953
Flight Test Ops	$21,225,000	$14,863,000	$12,021,000
Tooling	$158,900,000	$2,751,600	$608,240
Manufacturing Labor	$451,360,000	$32,571,000	$10,740,000
Quality Control	$38,052,000	$2,745,900	$905,430
Material & Equipment	$132,170,000	$9,579,300	$2,827,700
Engine Cost	$134,400,000	N/A	N/A
Total Cost	$1,135,000,000	$64,661,000	$27,482,000
Unit Sale	**$27,239,000**	**$19,398**	**$3,298**
Unit Flyaway	**$18,298,000**	**$11,912**	**$1,508**

The magnitude of the investment fits well within the global disaster preparedness system market size estimation of $160 billion (2022), which is expected to grow 8.5% annually through 2030 [17].

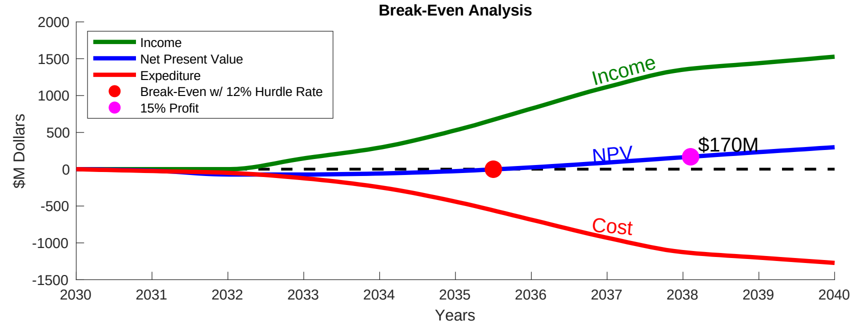


Figure 2.3.1: Break-Even Analysis

2.4 Support System Requirements

For logistics, Searchlight would be stationed within U.S. military bases abroad within areas that have high likelihood for earthquake occurrence such as Japan, Indonesia, India, Pakistan, Turkey, and San Francisco [18]. It can be assembled and deployed from the military base straight to the disaster sight. Hermes is designed to be stored alongside other task force equipment within cashes. Hermes will be transported alongside other task force equipment by FEMA standard; loaded into 463L pallets and transported by aircraft or truck depending on proximity to the earthquake [19]. LifeStar's light frame enables it to be transported along with search and rescue teams attached to their backpacks. Searchlight's technical support entails assistance during deployment and launch to ensure seamless startup. Real-time monitoring and control capabilities would enable tracking of the system's status and telemetry data [20]. The autonomous functionality of Hermes enables it to operate with minimal support. It will however require personnel to load the payload, perform repairs, and monitor its flight condition. LifeStar requires minimal technical support due to its robust design and user-friendly operation. Occasional support may be needed for hardware maintenance, software updates, and remote monitoring, but these tasks can be efficiently managed with a small team.

2.5 Connectivity Constraints

FEMA Chief of Tactical Emergency Communications stated in an interview with *The Last Mile*, "FEMA is able to support responders with satellite phones and data terminals along with mobile radio networks" [21]. As a result, AQERN will incorporate a combination of Wi-Fi, UHF, VHF, and satellite in its approach to communication. Searchlight will use Wi-Fi signals to connect directly to rescuers and allow them to access the information sharing website. In addition to rescuers, it will communicate to nearby Hermes drones in via UHF and VHF radio. UHF will be the primary form of connection and operates at low band 375-512 MHz to high band 764-870 MHz. VHF will be used when there is UHF interference and ranges from low band 49-108 MHz to high band 169-216 MHz [22]. Searchlight uses these UHF and VHF antennas along with its line of sight as an aerial system to repeat radio signals in the area and extend the effective range of existing radio communication systems. Finally, it will connect to its contingency remote-control station via satellite to ensure it can always be controlled regardless of range. Hermes drones will be able to connect directly to their monitoring stations at the BOO through UHF and VHF radio with antennas intended for beyond visual line of sight communication [23]. LifeStar drones will connect to the rescuers remote control through UHF radio for greater penetration through walls and obstacles.

2.6 Limitations Posed by Environmental Conditions

In the aftermath of an earthquake there are several potential environmental hazards to aviation-based technologies. For Searchlight and Hermes these hazards include strong wind, rain, and dust clouds. In the case of LifeStar, falling debris, obstacles, and dust clouds are the primary hazards. AQERN addresses all the individual hazards with various technologies for mitigation, summarized in Table 2.6.1.

Table 2.6.1: Mitigation of Effects from Environmental Conditions

System	Environmental Conditions	Impact	Technologies for Mitigation
Searchlight 	Strong Winds, Adverse Weather	Compromises flight stability	Stabilization System, Ground Anchor, Predictive Weather Algorithms [25]
Hermes 	High Winds, Adverse Weather, Dust Clouds	Alters delivery accuracy	Navigation System, Environmental Monitoring Sensors, Adaptive Flight Algorithms [26]
LifeStar 	Obstacles, Dust Clouds, Falling Debris, Adverse Weather, Low Light Conditions	Hinders ability to navigate and locate people	Dust resistant covers for gas sensors, remote monitoring, protective cage, LED light for lowlight/no light operation navigation

2.7 Expected Improvement Over Existing Practices

As stated in Section 1.2, the average survival rate drastically drops after the first 72 hours. Thus, challenges of inoperable communications, damaged supply infrastructure, and difficulty locating victims need to be addressed quickly. Searchlight will relay information between different emergency response teams, enabling communication during the 12 hours of operation. This allows rescuers and organizers a greater sense of situational awareness at all levels, enabling more informed decision making. After considering four different cities affected by the 2023 earthquake in Turkey and Syria, the average time for a truck to make a delivery from a probable BOO location to the city center was between 13 and 24 minutes seen in Table 2.7.1 [27]. Hermes can cover the same distance in 6-9 minutes without relying on roads, enabling faster and more consistent delivery to rescuers. LifeStar uses gas detection sensors and a camera so rescuers can safely and quickly find and analyze the locations of people and dangers both seen and unseen.

Table 2.7.1: Expected Improvements from AQERN

Challenges	Example	Improvement Method	Time Saved
Inoperable communication	Nepal 2023 – Communication loss, Helicopter Crash [27, 28]	Continuous radio communication	12 hours
Damage supply infrastructure	Turkey and Syria 2023 – Shortage of medical supplies [29]	Drone supply delivery	~ 13 minutes per delivery
Difficulty locating victims	Turkey and Syria 2023 – Victims buried under rubble for 7+ days [30]	Search and rescue tool	< 72 hours

2.8 Interoperability with Existing People, Organization, Solutions, and Technologies

As mentioned in Section 2.5, AQERN supports satellite and mobile radio networks, both of which are currently used in existing response operations during instances of communication loss. In addition, Searchlight supports multi-band radios and bandwidth switches, a solution currently used by FEMA for interconnection of systems [29,31] . This further demonstrates that AQERN can integrate existing FEMA personnel, solutions, and technology into its operations. Additionally, the team reached out to FEMA Emergency Management Specialist Lance Gilmore of the USAR Branch for insight on emergency and task force logistics and operations. In his email, Mr. Lance Gilmore States, "*GIS technology…allows the System to…determine the status of critical infrastructure, quickly prioritize target hazards, and assign adequate resources for reconnaissance and search operations.*" [32]. AQERN's system Searchlight can perform geographic information system (GIS) operations such as store, analyze, and interpret geographic data with its mapping system. Furthermore, its software would be compatible with common USAR products such as

Avenza Maps, Garmin, and SARTopo. In addition, Hermes can perform initial damage assessment upon reaching the disaster area, determining the status of critical infrastructure to provide insight on what emergency response teams can prioritize, and deliver necessary tools like LifeStar for search operations.

3.0 Pathway to Implementation by 2035

AQERN outlines a pathway to implementation by 2035 to meet responder needs by using high technology readiness levels, implementing current SAR team operations and FEMA management feedback, and conforming to procurement procedures.

3.1 Timeline to Implementation

The timeline in Figure 3.1.1 reflects manufactural, technological, and infrastructural advancements and its forecasted progression into the year 2035. AQERN begins with a manufacturing plan to set up a facility for tooling, initial production, and testing. By the year 2030, AQERN anticipates facility expansion with full-scale production the following year. While some of the technologies AQERN plans to employ are still in development, the team will monitor its progress to ensure availability and reliability by 2035 to continuously incorporate the latest technologies as it advances throughout the years. The Technology Readiness Level (TRL) for each respective technologies are justified in Table 3.2.1. For successful integration into the current infrastructure, AQERN's collaboration with stakeholders and the Federal Aviation Administration (FAA) are essential to acquire the necessary feedback, training and approvals needed to launch AQERN successfully by 2035.

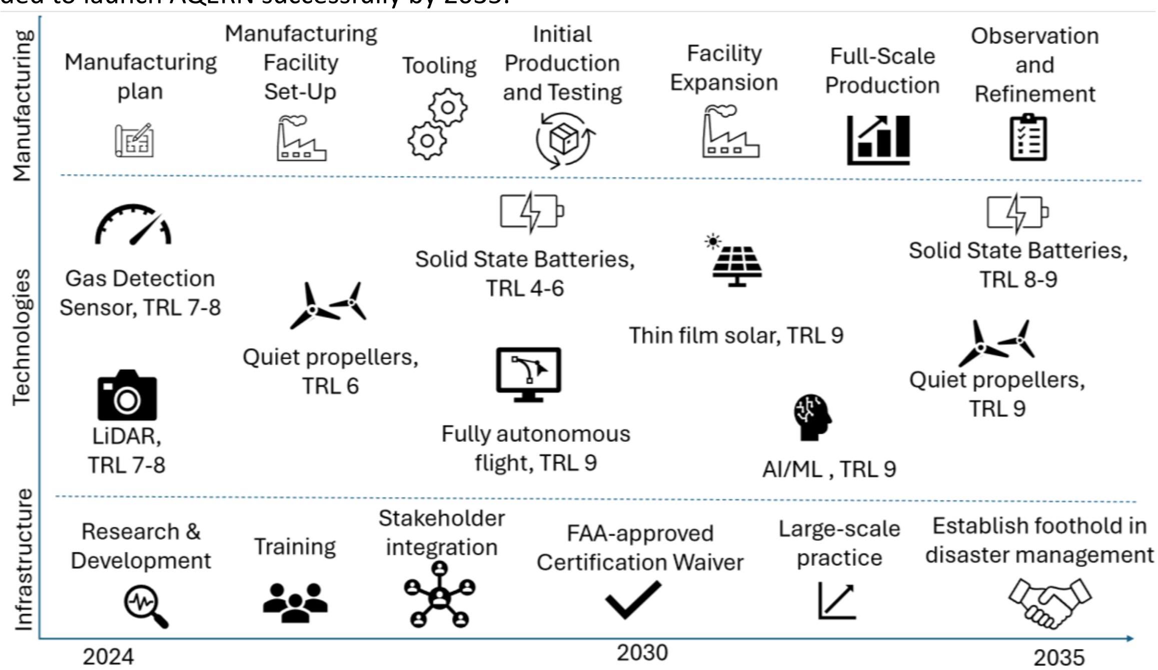


Figure 3.1.1: Aero-Quake Timeline to Implementation by 2035

3.2 Technology Readiness Level Progression

AQERN uses technologies with higher TRL levels that will be ready for use by 2035 (Table 3.2.1). AI and ML will be used in Hermes and Searchlight to rapidly analyze images & data, navigate fully autonomously, and support real-time decision making. Thin film solar is used in satellites currently, but their light weight and flexibility makes them good for airship applications while providing continuous power for long response missions. All systems will use SSD batteries for higher energy density. They are also less prone to catching fire, enhance safety, and charge much faster than traditional batteries, reducing downtime. Using LiDAR on Hermes will support AQERN with high-resolution mapping, rapid assessment of inaccessible areas, and provides accurate real-time data of surrounding obstacles. Combined with AI processing this can find possible ground routes for trucks as well. Finally, using a gas detection sensor on LifeStar will provide early warning for hazardous and flammable gases, assess air quality, and detect human life beneath rubble via traces of carbon dioxide.

3.3 Training

Effective training is essential for the earthquake response operational success of AQERN. Starting from 2026, every two years, AQERN will be actively participating in FEMA's National Level Exercise (NLE) [39] During NLE, AQERN joins operational planning and real-world exercises. Searchlight will be integrated into the existing exercise, and the operators and engineers from all parties will learn and practice how to efficiently launch Searchlight. AQERN also offers solutions to streamline operation training. Hermes autonomous flight reduces training time and eliminates the need for a dedicated pilot. Moreover, training times for LifeStar are minimized by using standard quadcopter controls and a user-friendly interface.

Table 3.2.1: Technology Readiness Levels

Technology	2024-30	2030-35
AI, ML [33]	6-7	9
Quiet propellers [34]	7	9
Thin-Film Solar [35]	6-7	9
SSB [36]	4-6	8-9
LiDAR [37]	7-8	9
Gas detection sensor [38]	7-8	9

3.4 Barrier Analysis

Risk identification to mitigate barriers in the implementation of AQERN is crucial. Environmental risks and mitigation were discussed in Section 2.6. Technical risks and their mitigation are discussed in Figure 3.4.1 and Table 3.4. For regulatory barriers, AQERN will work with relevant agencies such as the FAA to establish clear guidelines during procurement. As a civilian emergency response system, AQERN will utilize U.S. military, North Atlantic Treaty Organization (NATO) bases, and other hangars globally in earthquake-prone areas. This setup provides access to advanced technology infrastructure, expertise, and security. However, its dependency on military priorities may limit its responsiveness to civilian needs. Integrating AQERN into these bases requires careful diplomatic efforts, clear distinctions between military and civilian roles, and robust legal frameworks to ensure cooperation without compromising sovereignty or civilian priorities.

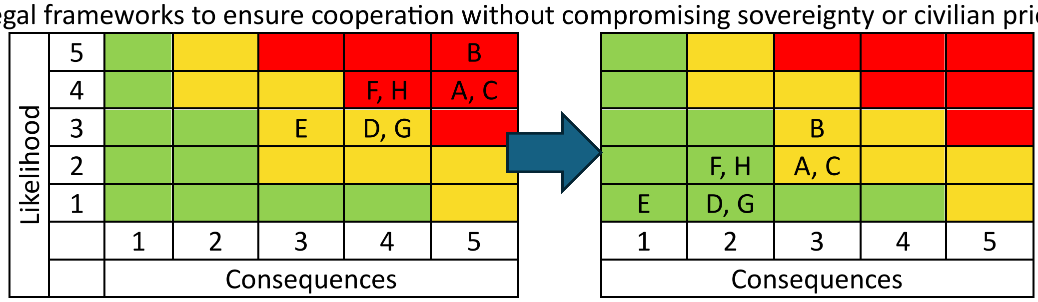


Figure 3.4.1: Risk Cube

Table 3.4 Risk Analysis

Risk	**Mitigation**
A: Comms. Interruption	Use a mix of communication channels (satellite, cellular, Wi-Fi) and advanced antenna technology at lower bandwidths.
B: Cyber Threats	Implement authentication protocols, end-to-end encryption, real-time monitors
C: Wi-Fi Signal Interference	Weather-resistant design like high-power output, redundant systems such as cellular network.
D: Battery Fire	Battery cell temperature management system, physical barriers between cells.
E: Delivery Failure	Improve the algorithm to determine landing locations and ready backup drones.
F: Battery Failure	More reliable batteries, advanced monitor battery health management.
G: Sensor Damage	Protective casings for sensors and cameras with filtering and sealing techniques.
H: Battery Depletion	Modular battery swaps, use SSBs with higher energy density, implement efficient battery management that optimizes power usage.

3.5 Customer/Stakeholder Operational Integration

Integrating AQERN with emergency stakeholders such as FEMA is started during the system's design phase. FEMA and others alike will form an advisory board and be an integral part of the AQERN development team to determine how the system's capabilities will align with the needs of the emergency response. AQERN will be connected to local emergency services through a ground command center. The data acquisition team will control and monitor the health and performance of Searchlight, Hermes, and LifeStar on the ground in real-time. Stakeholders will continue to provide feedback to AQERN throughout the development and test phases to make sure the operational procedures and responses are effective and timely for real-world situations. The scalability of AQERN was also designed in accordance with FEMA's National Urban Search & Rescue (US&R) Response System which consists of 28 task forces, containing 70 members each that operate within groups of 35 members [40]. The number of teams deployed varies per disaster based on severity, population density, and available resources which AQERN accounts for with Table 3.5 adjusting to however many task force teams are deployed.

Table 3.5.1: AQERN Scalability Based off of FEMA Deployment

System	Searchlight	Hermes	LifeStar
Units (Per 35 Member Team)	2	2	7
Units (Per Task Force of 70 members)	2	4	14
Units (Total for FEMA's 28 Task Forces)	2	112	392

4.0 Compelling Key Findings

AQERN uses modern and advancing technologies to improve rescue operations and dramatically increase rescue speed in the first 72 hours. Searchlight allows greater communication among all parties at the disaster, Hermes improves access to supplies and tools, and LifeStar increases direct search speed. Current USAR practices are well developed and well organized. However, they are not without room for significant improvement. Table 4.1 shows 7 key findings discovered during the development of AQERN.

Table 4.1: AQERN Key Findings

Finding #	Finding Statement
1	Aviation based systems are uniquely qualified to aid in earthquake rescue as they operate independently of ground conditions, an unpredictable aspect of earthquake response. And as of 2024 there are no UASs authorized for use or purchase through FEMA
2	Co-operation with international teams is an existing practice but information sharing, and multinational organization is not a given. This is a result of a lack of international standardization, language barriers, and limited infrastructure for communication
3	Searchlight offers a basis for communication in disaster areas by centralizing data which is vital for responder situational awareness. It also creates a standard for communication with multinational organizations and teams.
4	Hermes can reduce the delivery time of critical supplies like medical aid, food, and water by 70-80% (or saving 13 minutes from Table 2.7.1) compared to ground transportation in responding post-earthquake. Hermes also achieves an average speed of 55 mph, bypassing damaged infrastructure to expedite aid delivery to the five most vulnerable categories of people including injured individuals, elderly people, children, people with disabilities, and pregnant women.
5	Use AQERN's unmanned elements Hermes and LifeStar in responding to earthquakes, largely increasing safety for rescue teams, it offers 40-50% reduction in responder injuries.
6	From Table 1.6.1, SAR teams utilize heavy machinery to inspect areas with victims trapped beneath rubble. LifeStar can cover that same area at greater speed given its ability to enter hard-to-reach, dark areas through its gas detection sensor and LED lights [Section 2.6-2.7]

	and identify victims within 72 hours, potentially increasing the survival rate beyond 5% by the third day [Section 1.2].
7	AI technologies could reduce the personnel required to operate a fleet of Hermes drones from 4 to 1.
8	AQERN allows for uninterrupted coordination among rescue teams, significantly reducing response time by up to 12 hours.

5.0 Expanded Analyses Summary

Since the original proposal in February, expanded analysis has been done on trade studies for sizing, deployment and operational procedures, payload capabilities for Hermes, communication and bandwidth requirements for Searchlight, and structure of LifeStar to define a solution that is feasible and easy to implement without unnecessary cost.

Table 5.1: Changes from Original Proposal

Original Proposal	Addition or Change with Explanation
• Searchlight flies for 8 days.	• 8-day blimp was 2x larger than current blimps with power requirements; resized for a minimum duration of 72 hours with option to refuel/recharge.
• Only flyaway unit cost	• Added development, manufacturing, and operational cost from Raymer.
• Hermes focused on its own deliveries	• Added a benefit from Hermes' damage assessment capabilities that enables bulk supply deliveries from the ground
• Searchlight includes LiDAR	• Replace LiDAR with video since mapping and reflection from thousands of feet in the air can reduce accuracy. Reduces redundancy with Hermes LiDAR.
• Considered 4G, 5G, 6G, Wi-Fi 5-8	• 5 GHz Wi-Fi was selected over cellular for greater range and reduced equipment weight and power needs.
• Searchlight provides cell service to victims	• Providing cell service was found to be an expensive and heavy addition to Searchlight with limited benefits to responders and victims.
• Vague training	• Addition of simulation exercise in training timeline to prepare responders.
• Architecture structured on FEMA	• Factored in military and nonprofits to expand solution to more responder groups for a more realistic and holistic solution.
• Unknown fleet size	• Added a fleet size based on number of FEMA teams responding.

Appendix A: Figure References

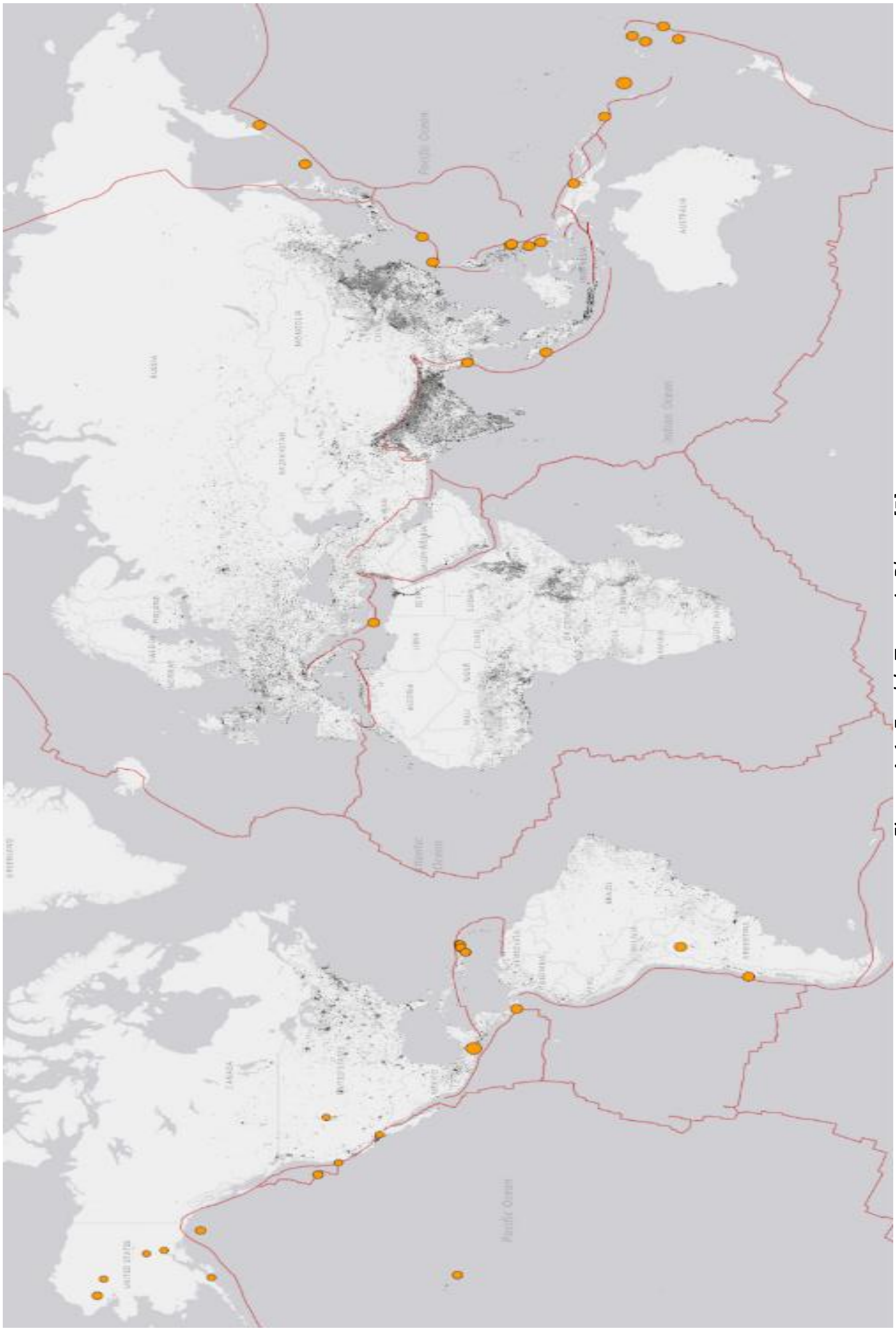


Figure A.1: Earth's Tectonic Plates [5]

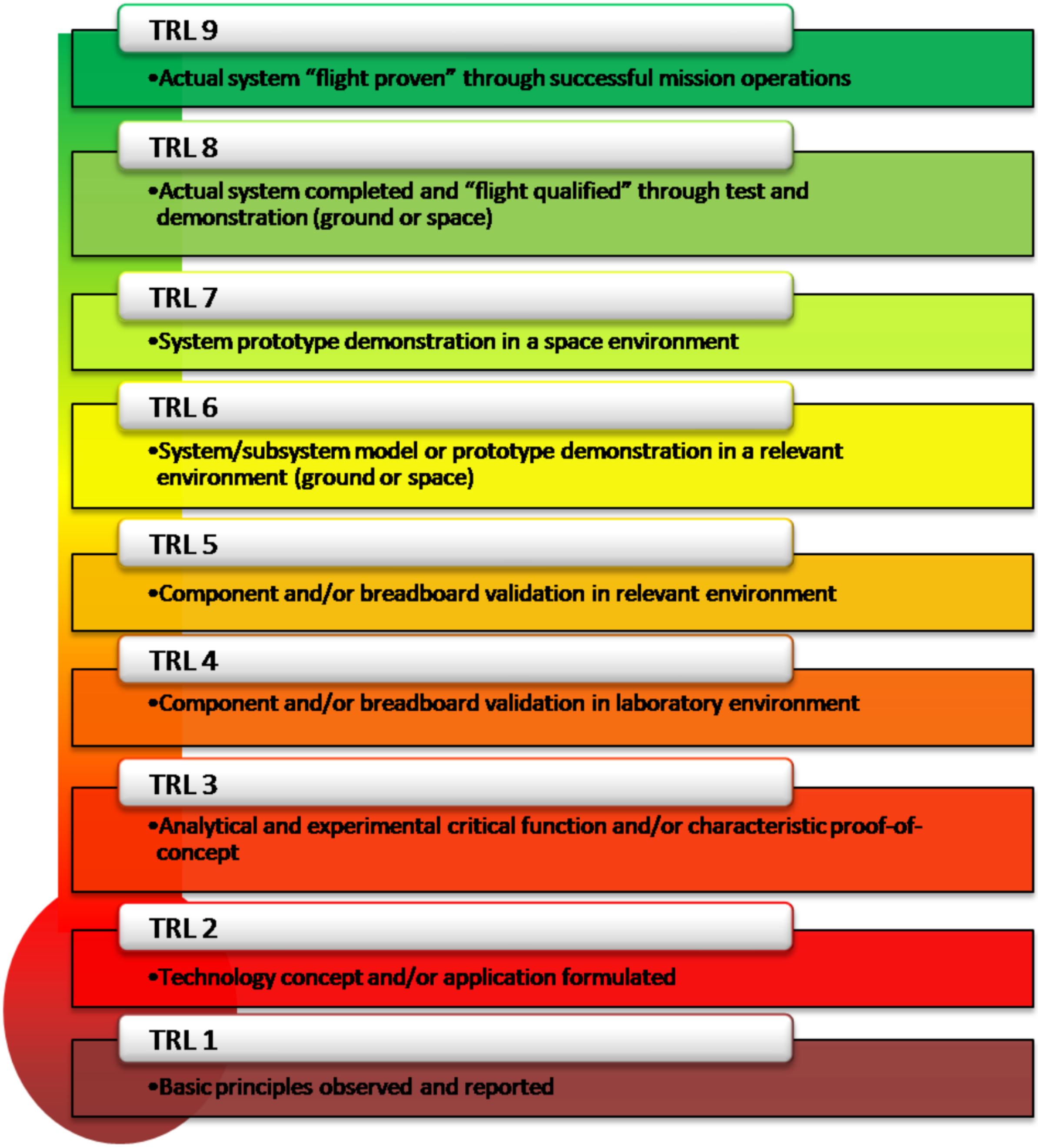


Figure A.2: NASA Technology Readiness Level Chart [42]

Table A.1: List of Technologies Taken from AQERN First Proposal

Technology Category	Current State-of-the-Art Example	Possible Application in AQERN	2024 TRL
AI [43]	Face/Voice Recognition Machine Learning Object Detection	Full Autonomy [44]	4
Reconnaissance	LiDAR [45,46] Synthetic Aperture Radar	Infrared Cameras [47] High Resolution Cameras [48]	9
Data Collection, Management and Dissemination	Satellite Communication 5G Technology [49]	UHF Relay, Satellite Connection	9
		4G, 2.4 Ghz Wi-Fi, 5G Technology [49], Li-Fi, Broadband	7
		Wi-Fi 8, 6G [50]	2
Virtual Reality (VR)	Surgical Training	Remote Simulated Training [51]	6
Augmented Reality (AR) [52]	Smart Glasses Spatial Computing	Remote Troubleshooting	8
Remote Sensing	Sonar NASA JPL FINDER [53]	Laser-based Spectrometer	9
		Gas Detection Sensor	8
		Plasmonic Sensor	4
Rapidly Identifying Areas in Need of Relief	Satellite Imaging GIS Open Data [45,47] Light Detection and Ranging (LiDAR) [46]	Light Detection and Ranging (LiDAR)[44, 46], Microphone, Speaker	9
		Topographic Mapping [53, 54]	7
		Real-time Mapping and Localization	4
		Long Range Terahertz Imaging [55, 56]	1
Energy, Power, Battery Density, Motor Efficiency	Lithium-Polymer and Lithium-Ion batteries	Solid State Batteries [56, 57] Quiet Propellers and Motors [57, 58]	5 ,7
		High Efficiency Thin-Film Solar Cells [58, 59]	9 [59]

Appendix B: System Trade Studies

<u>Searchlight Trade Studies:</u>

<u>Diesel vs Electric Propulsion Selection:</u>

Qualitatively, there is a lot more diesel resource in the world compared to electric. Military bases are typically stored with heavy fuel. Furthermore, to recharge an blimp would require responders to add much more time to their procedures, running the risk of not using the system at all. Recharging the blimp would Quantitively, with an estimate of 600 hp and 3 days of 12 hour motor use, the resulting battery needed for electric propulsion is about 107,000 lbs with a battery density of 330 Wh/kg. Meanwhile, with the current Searchlight weight estimate of 33,000 and a range of 2,000 nm, only 2,700 lbs of fuel are needed to keep the blimp moving.

<u>Antenna Feasibility:</u>

The estimated power required for an antenna to operate at a certain wavelength can be calculated from the Friss Transmission Equation. This was used to measure the feasibility of different communication methods such as cellular 4G/5G/6G and Wi-Fi 5, 6, 7, and 8 standards. These standards operate at certain frequencies. Today, the most utilized Wi-Fi standard is Wi-Fi 5 which operates at a 5 GHz frequency. After iterating through all the frequency ranges, it was decided that the best frequency to operate at is a frequency of 5.2 GHz, which is included in the Wi-Fi-6 standard today. New technologies being rolled out today operate on Wi-Fi 6.

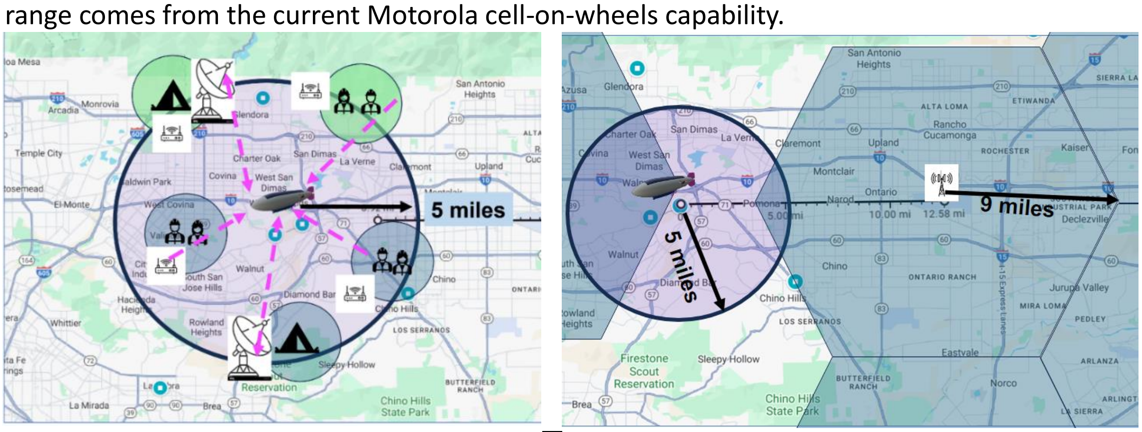
The Friss Transmission Equation is $P_R = P_t G_t G_r \left(\frac{l}{4\pi R}\right)^2$, where P_R is the power of the receiving antenna, P_t is the power of the transmitting antenna, G_t is the gain of the transmitting antenna and G_r is the gain of the receiving antenna, l is the frequency wavelength, and R is the distance between both antennas. A feasible antenna system would be:

Table B.1: Potential Antenna Values for a Responder Wi-Fi Network

Antenna Parameter	Value
Transmit Antenna Gain, G_t	30 dB
Transceiver Antenna Gain, G_r	0 dBi
Received Power, P_r	-60 dBm
Range	5 miles
Frequency	5.2 GHz
Transmit Power, P_t	3.1 W
Radiated Power	3.1 kWh

The radiated power is what is used to calculate the size of the battery. Battery size was calculated using estimates from **Figure B.2** of projected battery improvements in **Appendix B.**

Additional trade studies on how the communication network would work most efficiently were done. Two examples were Fig B.a. where larger antennas were placed at the BOO and responders were giving smaller portable units. Another option (Fig B.b.) was to use a blimp to fill where mobile cell-towers cannot. The 9-mile range comes from the current Motorola cell-on-wheels capability.



a. b.

Figure B.1: Visualization of Communication and Power Feasibility

Blimp Size Estimation:

The blimp size was calculated using simplified iterative methods from Nicolai & Carichner's *Fundamentals of Aircraft and Airship Design* textbook. A standard envelope of polyester was chosen to calculate the envelope weight. The weight breakdown of a blimp sized using a payload of a 2030 battery density of 350 Wh/kg is as follows:

Table B.2: Searchlight Weight Breakdown

Component	**Weight (lbs)**
Thin Film Solar Cells	350

Systems (Hydraulics, Electrical)	1,000
Gondola	1,155
Balloonets	1,300
Avionics	90
Antenna	65
Battery System	5,000
Envelope	10,764
Envelope Structure	5,511
Fuel	2,700
Engines	1,816
Septum	500
Camera	5
Total	**33,226 lbs**

Thin Film Solar

The current state of the art thin film solar operates at a power density of 450 W/kg. Its weight to area is 68.4 g/m^2. These were converted into lb/ft^2 to calculate how much power can be generated if they were integrated into 3% of the surface area of the envelope. This number was estimated from current airships which have successfully implemented thin film onto their envelope. The envelope surface area was calculated as 772,800 ft^2, of which 3% is about 25,000 ft^2. In total, this would amount to 350 lbs of thin film that produces 257 MW.

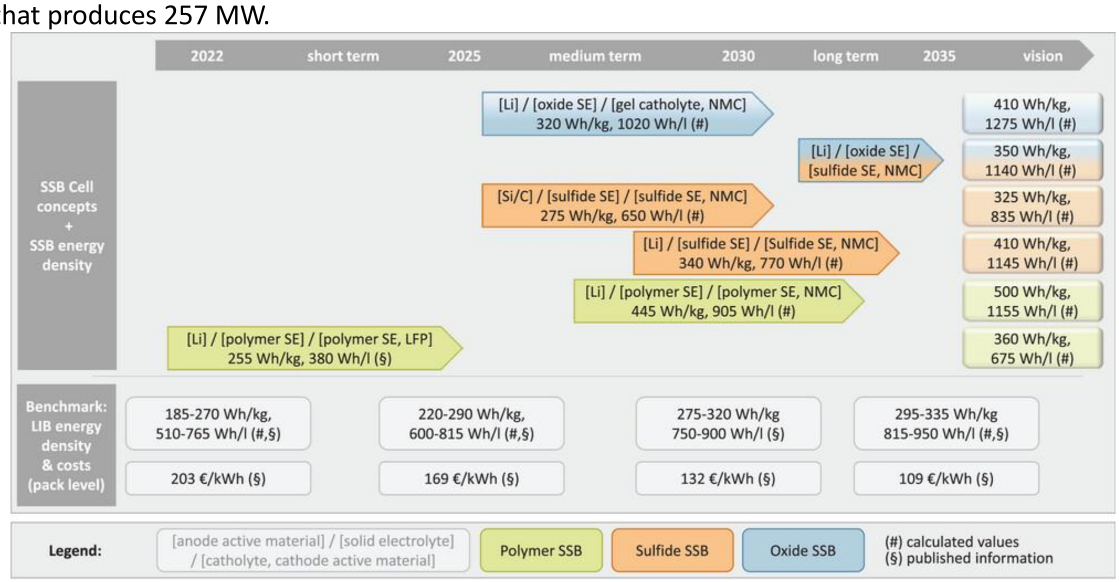


Figure B.2: Roadmap of future solid-state battery concepts [60]

Table B.3: Fabric Trade Study

Fabric Type	Pros	Cons	Source
Polyester	Does not mildew, high temperature resistance, greater airtightness, long lifetime (more than 1,000 hours)	Hard to find on open market	[61]
Nylon	Slightly lighter than Polyester	Fabric strength fades in couple hundred hours	[61]
Kevlar	Low weight, impact strength, low thermal expansion,	UV related degradation, high costs, difficult treatment, water/moisture absorbency, low compression strength	[62]

Polyurethane	More durable than polyester due to abrasion resistance, waterproof, high elasticity	Not as flexible as polyester	[63]

Hermes Trade Studies

Propulsion Trade Study

Even accounting for the most optimistic SSB energy density predictions. The added weight of a diesel engine is fare outweighed by the increase in performance it provides.

Table B.4: Hermes propulsion trade study

System	Weight (lbs.)	Fuel/battery weight (lbs.)	Endurance (hr.)	Efficiency
Electric	0.76.	10	3.5	6.73 g/W
Diesel	5.2 lbs.	7.6 (3.4 saved for VTOL battery)	8 h.	0.54 lb/hp.hr

Table B.5 is a summary of just some of the item's rescuers bring into the field and may need provided or resupplied during their 12-hour operation. Hermes payload size was determined to be 25lbs. so that it can accommodate all these items comfortably and have the option to take any combination of items to improve the efficiency of the system.

Table B.5 Hermes Payload Sizing Table

Payload	Contents	Weight (lbs.)
First aid pack	Wide range of first aid medical supplies	22
Blood transfusion	Blood, plasma, platelets, Blood administration kit	4
Exposure treatment	Meal replacement bar x2, 16oz water bottle, neoprene blanket	3.25
LifeStar	LifeStar, replacement battery 2x	8
Battery resupply	300Wh portable charger, power tool batteries x 4	15.7
Sensor supply	Movement detector, spare batteries x2	18
	Bore camera/microphone, headphones x2	6.4
	Wired seismic sensors x3, wireless seismic sensors x3	15

Hermes uses quiet propellers to avoid noise interference with ground crew operations. Table B.6 summarizes the differences between different propeller designs. Toroidal propellers were selected due to their good basis of research and noise reduction effects in addition to their increased efficiency.

Table B.6: Hermes Propeller Trade Study [60]

Propeller type	Noise reduction(dBA)	Pros	Cons
Standard 4 blade	0	Easily available, cheap to manufacture, well known	No noise reduction, annoying to ground crews
Toroidal	10-15	Solid noise reduction, solid base of research 2-4% increase in efficiency	Increased manufacturing cost
Asymmetric	~	Qualitative studies show amazing noise reduction, Easy to manufacture	Very small base of research, vibrational issues at low to mid rpm range

LifeStar Trade Studies

Gas Detection Study

As rescue scenarios can be so vastly different it is not realistic to detect all gasses. Detecting more generally dangerous gases like hydrocarbons and carbon monoxide is important in all rescue scenarios as they pose large threats and are very common. However, allowing modularity is important so rescuers can adapt to their own needs. For instance if a rescuer is searching a collapsed fertilizer plant there are different detection requirement from searching a residential property.

Table B.7: Weight and Monetary Cost of Detecting Various Gasses

Gas	Per-Unit Cost to detect	Weigh of required sensor (g)
Carbon monoxide	$6	3
Carbon dioxide	$15	4
Methane	$5	9
Propane	$5	9
Gasoline	$5	9
Modular port	~	2

Propeller Selection

Toroidal propellers were selected for LifeStar as they increase endurance and reduce noise when compared to a standard 4 blade drone propeller as seen in Table B.8

Table B.8: LifeStar Propeller Selection

Propeller type	Endurance (min)	Noise Reduction
Standard DJI prop	43.3	0
Toroidal Propeller	45.6	10-15 dBA

Camera Selection

The pros and Cons of adding an additional camera are summarized below in Table B.9. The addition of an infrared camera increases visibility in dusty and dark areas while only slightly adding to total sensor power draw. However total sensor power draw is a miniscule portion of the power draw for LifeStar and as such would not significantly affect endurance.

Table B.9: LifeStar Camera Type Trade Study

Camera layout	Total power draw	Added weight(g)	Total cost
Visual spec camera	85mA	9	$30
Visual spec camera + LEDs	95mA	.5	$33
Infrared camera	80mA	22	$150
Visual spec + infrared camera	165mA	31	$180

Appendix C: Cost Calculations

As mentioned in Section 2.3, the cost calculations were performed using the Rand Corporation costing method [16]. Using the Rand Corporation method as the foundation, a program was developed using MATLAB to complete the cost estimates. The program not only calculates the costs, but also performs the net present value & break-even analysis.

Figure C.1: Inputs used for cost calculations

```
%Variables
%          SL      HM      LS
W     = [33000    50       9];  % empty weight in pounds
S     = [   60    47.4    26];  % maximum speed (kt) at best altitude
Q_D   = [    5    25      50];  % number of development flight test aircraft
Q_P   = [   45  3975    9950];  % number of production aircraft;
Q      =  Q_D + Q_P;            % cumulative quantity produced
price = 1.20;                   % Price for selling products
```

Figure C.2: Rand Corp. *Costing* Equations

```
Cumulative airframe engineering (2024 dollars)
  E_hours = 4.86 * W.^0.777 .* S.^0.894 .* Q.^0.163;
  E_cost  = E_hours * (2.576 * 2024 - 5058);
Development support cost (2024 dollars)
  D_cost = 1.92 .* 66 .* W.^0.63 .* S.^1.3;
flight test operations cost (2024 dollars)
  F_cost = 1.92 .* 1852 .* W.^0.325 .* S.^0.822 .* Q_D.^1.21;
Tooling (2024 dollars)
  T_hours = 5.99 .* W.^0.777 .* S.^0.696 .* Q.^0.263;
  T_cost  = T_hours * (2.883 * 2024 - 5666);
Manufacturing labor (2024 dollars)
  L_hours = 7.37 .* W.^0.82 .* S.^0.484 .* Q.^0.641;
  L_cost  = L_hours * (2.316 * 2024 - 4552);
Quality control hours (2024 dollars)
  QC_hours = 0.076 .* L_hours;
  QC_cost  = QC_hours * (2.60 * 2024 - 5112);
Manufacturing material and equipment costs (2024 dollars)
  M_cost = 1.92 .* 16.39 .* W.^0.921 .* S.^0.621 .* Q.^0.799;
Engine unit cost (2024 dollars)
  P_cost = [1.92 * 700000 * 2 * Q(1), 0, 0];
Total cost
  t_cost = E_cost + D_cost + F_cost + T_cost + L_cost + QC_cost + M_cost + P_cost;
  t_cost_unit = t_cost./Q;
  t_cost_sale = t_cost_unit*price;
Flyaway cost
  f_Cost = (T_cost + L_cost + QC_cost + M_cost + P_cost)./Q;
```

Table C.1: AQERN vehicle production numbers

Production numbers by year										
Year	1	2	3	4	5	6	7	8	9	10
Searchlight	1	1	3	5	8	10	10	8	3	3
Hermes	80	80	240	360	600	800	800	600	240	200
LifeStar	200	200	600	900	1500	2000	2000	1500	600	500

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