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Project Closure Report

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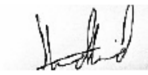
Project manager	Andy Hampsey	Signature: 
Project sponsor	Andy Carnall	Signature: 
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1. Project Description

1.1. Abstract

The decarbonisation of the construction, mining, and quarrying sectors is a key challenge in achieving the UK's net-zero emissions target.

Compressed hydrogen fuel can be a direct replacement to red diesel supplying fuel cell powered or ICE applications. Its high energy density can power a variety of nonroad mobile machinery. The current cohesion of a hydrogen supply chain is a limiting factor for industries as it is affecting the accessibility and price per kg of hydrogen for the end user.

However, the lack of infrastructure for hydrogen refuelling has been a barrier to its adoption. The development of mobile hydrogen refuelling stations can provide a flexible and cost-effective solution to this challenge. By deploying mobile refuelling stations in strategic locations, the adoption of hydrogen fuel cell vehicles and equipment can be accelerated.

Moreover, the development of mobile hydrogen refuelling stations can have benefits in other hard-to-abate sectors, such as heavy-duty transportation, shipping, and aviation. By using mobile refuelling stations, hydrogen powered applications can be deployed more widely, reducing their reliance on fossil fuels, and contributing to the decarbonisation of these sectors.

The use of hydrogen can also have economic and environmental benefits, such as improving energy security if produced domestically, improved air quality in urban areas due to low carbon emissions at point of use and reduction in noise pollution. Collaborative efforts between government, industry, and academia will be crucial to accelerating the deployment of mobile hydrogen refuelling stations and achieving the UK's net-zero emissions target.

1.2. Background

Construction and mining vehicles are significant contributors to carbon emissions due to their size, power, and usage patterns. These vehicles are typically heavy-duty and require high levels of energy to operate, resulting in significant emissions of carbon dioxide and other greenhouse gases. Applications in this sector typically operate at various sites with minimal permanent infrastructure and away from built up areas. They require fuel to come to site.

The primary source of emissions from construction and mining vehicles is their operation, as they are typically run-on fossil fuels such as diesel. The combustion of these fuels' releases carbon dioxide, nitrogen oxides, and particulate matter into the atmosphere, contributing to climate change and air pollution. Heavy-duty vehicles, including construction and mining equipment, are responsible for a disproportionate amount of these emissions due to their high fuel consumption and low fuel efficiency.

For example, in the US, a potential future market for Pioneer deployment, there are over 2 million pieces of construction and mining equipment which consume over 22 billion litres of diesel fuel each year. Whilst the absolute numbers in the UK will be smaller the impact on the environment is not localised to the area of emissions, especially in the case of CO2.

From the competition summary, red diesel is mainly used in non-road mobile machinery (NRMM) which accounts for 6 MtCO2 annually. Burning a litre of diesel produces around 2.6kg of CO2. This equates to 2.3 billion litres of red diesel used for NRMM activity in the UK annually. Diesel produces ~3 kWh of energy per litre burned assuming a conventional combustion engine with 30% efficiency hence red diesel for NRMM activity requires an energy requirement of 6.9 billion kWh which equates to 24.7 billion MJ. This results in a 6 $MtCO_2$/24.7 billion MJ = 243 gCO_2e per MJ (considering other aspects of the well to work chain like production, refining, pumping etc the higher 266 gCO_2e/MJ value in the guidance form is clear).

Transporting the red diesel in large tankers to and from site is the most efficient current practise without building a diesel refinery. Assuming a 50km distance from the diesel source to the refuelling site equates to a 100km round trip. On average a modern-day lorry consumes 29.8 litres of diesel per 100km. Assuming large diesel tankers of 36,000L are transported per trip, this results in an extra 5 million kgs of CO_2 emitted which is insignificant compared to the 6 $MtCO_2$ and hence does not impact the 243 gCO_2e per MJ value.

In an extreme case that all red diesel powered NRMM vehicles transition to hydrogen fuel cell technology then there would be 0 gCO_2 per MJ for using this machinery. Fuel cell technology does not emit emissions at point of use, it converts hydrogen and oxygen (from the air) into electricity and harmless water. This does not account for the kg of CO_2 emitted when transporting hydrogen to and from site. Transporting the hydrogen to and from site is mirroring the current practise of delivering and dispensing diesel. Knowing that hydrogen produces ~16.5 kWh of energy per kg reacted assuming a fuel cell engine with 50% efficiency and the energy requirement is 6.9 billion kWh, this equates to a need for 416 million kgs of hydrogen gas. Using the same parameters for the red diesel transport: 100km round-trip, modern-day lorry uses 29.8 litres/100km, a litre of diesel releases 2.6kg of CO_2 are used, it is calculated that the Pioneer solution would take 1.4 million trips to deliver the hydrogen required. This results in an extra 108.3 million kgs of CO_2 emitted from transporting this hydrogen. The hydrogen transported has a total MJ worth 24.7 billion and results in 4.4 gCO_2e per MJ.

In the competition guidance the well to work value for gaseous hydrogen compressed to 88MPa is 1.7 gCO_2e/MJ. With the Pioneer solution, the Pioneer is filled with high pressure hydrogen specifically 50MPa) and then transported to site for refuelling. Hence the well to work value becomes 6.1 gCO_2e per MJ and taking a relatively worst-case fuel cell efficiency of 50%, the well to use value becomes 12.2 gCO_2e per MJ. Comparing to red diesel (266 gCO_2e per MJ) hydrogen has 20x lower gCO_2e per MJ when powering.

In addition, NRMM application to contribute carbon emissions through their usage patterns. These vehicles are often used in remote or hard-to-reach locations, requiring significant transportation to get them to and from job sites.

1.3. Impact of Project

Decarbonising the construction, mining, and quarrying sectors is a vital step towards achieving the UK's climate goals. One solution to reducing reliance on fossil fuels is to transition to compressed hydrogen as a fuel source. Compressed hydrogen is a zero-emission fuel that can be produced from renewable energy sources, and it has a high energy density, making it a strong contender for this application.

This project aims to develop a solution which will allow for the decarbonisation of these sectors.

Alternative fuel vehicles must be cost competitive and functional to stand a chance in the free market. One of the challenges of transitioning to compressed hydrogen as a fuel is the lack of infrastructure to support it. Hydrogen fuelling stations are expensive to build, and the UK currently has a limited number of them.

NanoSUN has recognised these issues and developed a mobile solution known as the Pioneer. The Pioneer is a low cost, mobile hydrogen refuelling station that stores, transports, and dispenses hydrogen from the point of production to the point of use in a single package. This functionality is integrated in a single 20ft container and acts as key component of the hydrogen supply chain. When partnered with hydrogen production and compression players, the Pioneer can provide a full hydrogen well to use operation with end use prices competitive to white diesel.

They can be transported to construction sites, mining operations, or quarries and can be powered by renewable energy sources such as solar or wind, making them a sustainable solution. Additionally, they can provide a cost-effective alternative to building permanent refuelling stations, which are expensive, time-consuming to construct and may not provide a suitable return on investment. They allow hydrogen to be sourced from multiple providers, allowing competition to drive down the cost of hydrogen molecules.

They also increase the utilisation of fixed infrastructure which provides multiple benefits as:
It strengthens the business case for new construction.

- This helps develop critical infrastructure to allow widespread adoption.
- Greater adoption leads to economies of scale.
- It will encourage new entrants into the market bringing new technology.

All this is done while providing a service to the construction and mining industries, reducing their global impact, and providing a flexible solution which can be scaled to the demand of the sector.

1.4. Impact on other sectors

The development of this project will also have the potential to benefit other hard-to-abate sectors, such as heavy-duty transportation, shipping, and aviation.

One of the challenges of decarbonising heavy-duty transportation is the lack of infrastructure to support zero-emission vehicles. Hydrogen fuel cell trucks and buses have the potential to replace diesel-powered vehicles, but the lack of refuelling infrastructure is a major barrier to their adoption. Mobile hydrogen refuelling stations can provide a cost-effective and flexible solution to this challenge. By deploying mobile refuelling stations in strategic locations, such as at service stations or rest areas, the adoption of hydrogen fuel cell trucks and buses can be accelerated.

The shipping industry is responsible for a significant portion of global emissions, and decarbonising this sector is essential to achieving the goals of the Paris Agreement. One solution to decarbonising shipping is the use of hydrogen fuel cells to power ships. Again, the lack of refuelling infrastructure is a major barrier to the adoption of this technology. Mobile hydrogen refuelling stations may not themselves be suitable due to the large hydrogen demands of this sector however they can pave the way for large scale fixed infrastructure to be developed at ports which can then become hydrogen hubs for fuelling Pioneer systems.

The aviation industry is another sector that could benefit from the development of mobile hydrogen refuelling stations. Decarbonising aviation is a significant challenge. However, hydrogen can be used as a fuel for ground vehicles and airport equipment, such as baggage tugs and catering trucks. Development of hydrogen powered aircraft is ongoing and mobile refuelling stations can support that development.

The development of mobile hydrogen refuelling stations has economic benefits. The deployment of mobile refuelling stations creates new jobs in the hydrogen economy, such as the operation and maintenance of the refuelling stations. The design and development of these systems utilises the engineering talent of the UK and provides a pathway for technical staff currently working in the oil and gas industry to transition to lower emissions projects. It also strengthens the UK's position as a global leader in research and academia. the emerging field of hydrogen technology is anticipated to grow substantially in the coming years, and investing in research and development will enable the UK to become a leader in this growing industry.

Secondly, by developing and deploying innovative technologies such as Pioneer Systems, the UK can reduce its carbon footprint and address its climate goals, demonstrating leadership in the fight against climate change.

Additionally, as hydrogen is expected to become a critical component in the energy mix of the future, investing in research could help the UK secure its energy supply and energy independence.

Finally, by fostering partnerships between academia, industry, and government, the UK can establish a collaborative and innovative ecosystem that is conducive to further scientific breakthroughs and technological advancements in hydrogen technology.

1.5. Project Methodology

The current Pioneer solution has been prototyped for on road use and on road hydrogen applications. This project with BEIS will look to develop the existing Pioneer blueprint specifically for offroad environments and for NRMM applications through the following two objectives:

1. The first objective set was to conduct a concept viability evaluation by Investigating the effects of transporting the Pioneer on offroad conditions by conducting offroad shock & vibrational (S&V) testing to an industry standard on the gas manifold subassemblies. Each subassembly will be pressurised to above its intended working pressure after each S&V test assessing the effects on gas tightness. The results will be assessed, and any design improvements will be fed into the preliminary design process for an offroad Pioneer. This is covered by work package 2 & 3.

2. The second objective was to complete the preliminary design of Pioneer to meet the large demands of various hydrogen NRMM on site. The work in the project would develop the operational aspects of the Pioneer for the chosen environment allowing it to play a crucial role for sectors to transition away from red diesel and towards a sustainable alternative in hydrogen. This product variant for the sake of this project was code named P150. This is covered by work package 4.

The main deliverables for the design phase were:

- Identifying suitable cylinder suppliers
- Generating a provisional P&ID
- Generating an initial Bill of Materials
- Generating a provisional 3D model of the design.

The applicability of the Pioneer blueprint for offroad transportation and NRMM refuelling is unknown, and hence the technology is at TRL 4. By completing the afore mentioned objectives, this will push the P150 offroad to a TRL 5. The design work will continue post project completion with the intent for TRL 6 prototype development in Phase 2.

2. P150 Product Concept

2.1. Abstract

The development of a P150 Mobile hydrogen refuelling system (mobile HRS) has highlighted numerous benefits to help decarbonise the construction, mining, and quarrying sectors. Alternative solutions include:

- other mobile hydrogen refuellers,
- fixed infrastructure for dispensing hydrogen,
- battery electric vehicles

All these would assist in reducing or even eliminating emissions at point of use, improving air quality, and reducing noise pollution. Other options can result in a reduction of emissions which include things like operation changes, alternative fuels, and hybridisation.

The P150 solution is however not without its own challenges, some of which are more significant than others. Major challenges facing P150 include the availability of green hydrogen across the UK, the availability of equipment and components at the required specifications, the interaction between different legislative frameworks and how they apply to mobile refuelling stations. Other challenges include, ensuring the equipment performs reliably, having a positive user experience, ensuring the costs are reasonable and getting external support in validating and certifying the Pioneer package.

2.2. System Benefits

There are several identified benefits of the P150 solution compared with the primary alternative of a permanent refuelling station. Other options that have been compared against in some instances are battery electric vehicles and changes in operational behaviour.

2.2.1. Cost

The P150 system offers cost benefits compared to fixed infrastructure for construction sites. Firstly, mobile stations can be more cost-effective, as they require less equipment and infrastructure to be installed. For inner city construction sites where a fixed refuelling station is not already present, the cost of the land required to construct a refuelling station could be prohibitive, to recoup the cost the station could be opened to the public, but this creates a wide array of significant other issues such as safety, security, and access requirements. In rural areas where mines and quarries are more likely to be located it is unlikely there would be enough demand for a fixed refuelling station to recoup the cost of construction.

Mobile stations can be rented or leased on a short-term basis, allowing companies to avoid the high upfront costs of installing fixed infrastructure. This can be particularly advantageous for companies with shorter-term projects or uncertain demand for hydrogen fuel.

NanoSUN Mobile HRS design provides cost savings through reduced transportation expenses. By bringing the fuel to the site, rather than having to transport vehicles to a fixed refuelling station, companies can save on fuel costs, vehicle maintenance, and time.
Overall, while fixed infrastructure has its advantages, such as greater capacity and availability, the cost benefits of mobile hydrogen refuelling stations make them an attractive option for many construction companies looking to adopt hydrogen technology.

The other option for zero emissions at point of use is battery electric vehicles, the cost of electricity for charging BEVs is typically lower than the cost of hydrogen fuel, which can be a significant factor in the long-term cost analysis. However, there are several other factors which need to be considered such as, the cost of transmission of electricity to remote areas,

the infrastructure requirements for charging vehicles which can add significantly to the total cost, the speed of refuelling and whether large NRMM applications can be designed with batteries for the intended operations.
Depending on the operating parameters of the site the time taken to charge battery vehicles may mean an excess of vehicles is required as they will be unavailable for significant portions of their life while being charged. There is also the cost to productivity if the vehicles are unavailable when required as the batteries take several hours to charge. The P150 does not have this issue as it can refuel vehicles in a matter of minutes and if greater fuelling speeds are required the system has been designed to include modules which can further increase its performance in this area.

Cost savings for changing operation behaviour are less clear cut and if cost benefits can be realised via a change in operational behaviour, then those benefits would also be available to users of both electric and diesel vehicles. Examples of this would be less idling time or choosing more direct routes. Regardless this is good practice that should be implemented where possible in all cases.

2.2.2. Flexibility

When it comes to flexibility, there are significant differences between P150 and fixed hydrogen stations for construction sites. While mines and quarries are generally fixed with a well understood long term demand for fuel, construction sites can vary significantly across the build process.

P150 systems offer a high degree of flexibility as they can be transported to separate locations, making them ideal for temporary construction sites or projects that require mobility. They can be quickly deployed and removed, allowing companies to respond quickly to changing demands.

P150 has also been designed with modularity and expandability in mind. A small P150 system can be used where the demand for hydrogen is low, as the demand increases the system can grow to accommodate the demand. [redacted] As a project winds down the different modules of the P150 system can be gradually deployed to other projects so infrastructure is not going unused or underutilized.

Due to the fast-refuelling speed hydrogen is a more flexible solution than battery electric assuming the supply of hydrogen is readily available. The major challenges of managing tank temperature to improve refuel speed are addressed by the optional heat exchanger designed into P150 which allows fuel cooling by integration with other NanoSUN products.

Where facilities operate multiple vehicle types P150 is able to dispense to either 350 and 700 bar vehicles depending on the chosen configurations. It should also be noted that the P150 system has been designed to interface with electric vehicle charging equipment and so it does not have to be an either/or situation. P150 has the flexibility to support both hydrogen powered vehicles in addition to battery electric.

2.2.3. Manufacturability and Serviceability

The P150 has designed to be a reproducible product, by taking a modular design approach it can be constructed off site by multiple manufacturers. The design has been simplified from other mobile refuellers and the space envelope for process equipment expanded to aid in the assembly process. This has the added benefit of improving the serviceability of the equipment, as greater access is provided to the various components and the separation into modules means that should a module fail to operate as expected it can be rapidly exchanged allowing the rest of the P150 system to continue operation. This is unlike fixed infrastructure where a component fault may render the entire station inoperable for a prolonged period until a fix can be enacted.

The system has been designed to allow multiple sourcing of components, providing robustness to the supply chain, and allowing negotiation for effective pricing. It also reduces the risks in servicing where a substantial number of spares must be carried in the event that a component is no longer available.

The P150 struggles in terms of manufacturability and serviceability compared with battery electric vehicles as the technology is simpler and more readily understood in the case of the latter.

2.2.4. Emissions

P150 allows construction and mining vehicles to operate with green hydrogen. Green H2 is generated from renewable sources and as such eliminates carbon emissions in production and use. The primary emissions from the use of H2 as a fuel are heat and water. The reduction of emissions on construction and mining sites is a positive impact for both the planet and the people working on and around these sites.

The transport of P150 could also become zero emission in the case that hydrogen or battery powered vehicles are used when transporting the unit between mother stations and the operational point. To facilitate that there has been a significant reduction in the weight of the system by using Type 4 CF cylinders.

These are benefits of using P150 over hybrid vehicles or changing usage patterns however the impact compared to battery electric or fixed stations is minimal.

2.2.5. Connectivity

P150 has been designed with data at its heart, by construction site operators using P150 systems NanoSUN will be able to advise on how best to operate their fleet to maximise efficiency and utilization. This additional functionality would not be available to users of other mobile refuellers, users of static stations or users of BEV's.

2.3. System Challenges

Whilst there are a number of benefits to the P150 and mobile refueler concept in general there are also a wide array of challenges.

2.3.1. Hydrogen Economy

The hydrogen economy is still developing and although growing at a rapid pace funding and incentives must continue to be granted to stimulate this growth. A major burden for the adoption of hydrogen is its availability, both locally and nationally. For P150 to succeed it requires stable supplies of H2 at pressures which make for an effective refuelling system.

P150 is able to fuel both 350bar and 700 bar vehicles however in order to fuel the latter effectively high-pressure gas sources at supply depots are required. Whilst NanoSUN has the capability of compressing hydrogen to high pressures the use of this facility to support all P150's is unreasonable. The challenge to the development of these systems is often one of utilisation and so P150 will help to develop this infrastructure as it becomes a customer of it, however until the infrastructure becomes available, we face challenges to how we operate the systems.

2.3.2. Equipment Availability

One of the challenges of mobile hydrogen refuelling stations is the availability of equipment that is suitable for use in a mobile setting. Mobile hydrogen refuelling stations require specialised equipment that can handle high-pressure hydrogen storage and dispensing, as well as monitoring and safety equipment to ensure safe and reliable operation.
One of the key pieces of equipment required for mobile hydrogen refuelling stations is the hydrogen storage tanks. These tanks need to be lightweight and durable enough to withstand the rigours of transportation, but also large enough to store enough hydrogen to meet the refuelling needs of vehicles. New tanks are currently in development, but many are designed with vehicles in-mind. In order to operate a cascade refueller it is better to have a pressure above that of the target pressure of the vehicle.

There is also the challenge of suitable valves which can operate at the temperatures and pressures required, whilst at the same time having a low power draw to enable off grid applications of P150. In order to get the highest utility it is essential to minimise pressure losses and so fining components which have low restrictions is also a high priority.

Process equipment is not new however many components have not been tested and validated with hydrogen. When we have come to experiment with unproven equipment, we have found unexpected leaks and failures due to the propensity of hydrogen to escape and its effects on materials such as O-rings and carbon steels.

2.3.3. Legislative Frameworks

Right now, there is an array of regulations which can apply to mobile hydrogen refuelling stations however separating out which do apply, and which are not relevant to this application can be challenging. It would be helpful if there was clearer guidance and alignment between standards applied to pressure equipment, transportable pressure equipment, fuelling stations and vehicles. In many cases the overlap is not well understood and the requirements to comply can be in conflict. It would be helpful if clear guidance was given either by the government or certified bodies to facilitate development.

2.3.4. Reliability

Significant effort is required to ensure P150 is built to withstand the stresses and strains of an offroad environment. Pressure equipment is not often expected to undergo these types of loads and the P150 system has transportability as a defining feature. The use of anti-vibration components and mounts is one aspect which has been factored into the design. The testing and understanding of systems and panels ensures that when the P150 is in the field operators can have confidence it is fit for purpose.

2.3.5. User Experience

For widespread adoption to occur the user experience is paramount. P150 is designed to be simple and easy to operate with minimal training and exposure required. We have taken lessons learned from our existing portfolio and applied this to the design however challenges remain. For operation safety we must maintain barriers between electronics and process equipment, and having a fully mobile system means that the units may be permanently mounted on the back of a truck. These present ergonomic challenges and operational issue which can degrade the experience of a P150 user. We address these challenges though a [redacted] and consultation with the operator so that we understand their use case and can specify a P150 to match. Should the use case change the flexibility in P150 allows us to adapt to their new needs.

2.4. P150 Preliminary Design development

2.4.1. Background

The purpose of this report is to explain the reasoning behind the technical decisions made during the concept and initial development stages of the P150 system.

The development of the P150 mobile hydrogen refuelling system began with an analysis of market requirements. This involved conducting a survey to gather feedback from potential customers and stakeholders, which helped to identify key features and requirements for the product. Using the market requirements as a foundation, the engineering team then developed a set of technical requirements based on experience and industry best practices. This involved identifying key performance parameters such as flow rate, pressure, and capacity, as well as considerations for safety, reliability, and ease of use.

With the technical requirements established, the team began investigating potential cylinder suppliers and developed a database of cylinders that met the necessary specifications. This involved evaluating different cylinder materials, sizes, and configurations to identify the most suitable options for the P150 system. Using the information gathered from the cylinder investigation, the engineering team developed a preliminary P&ID (Process and Instrumentation Diagram) that outlined the system's key components and how they would be connected. This provided a blueprint of the system and allowed for the development of a Bill of Materials (BOM), which included a list of all the necessary components and materials required to build the system.

The P&ID and BOM were used as a foundation for the creation of a 3D concept model using industry leading modelling tools. This allowed the engineering team to visualise the system in a realistic and detailed way and identify potential design issues and improvements. Multiple parallel concept models were developed and compared to select the best design option.

Throughout the development process, the team employed various engineering methodologies, including HAZOP, LOPA and DFX (Design for X), to ensure that the product was designed with safety, reliability, and manufacturability in mind.

The final concept design, the P150 mobile hydrogen refuelling system, was the result of a rigorous development process that incorporated customer feedback, industry best practices, and engineering methodologies. By leveraging advanced modelling tools, the team was able to create a highly efficient and optimized design that met the needs of customers and stakeholders while adhering to strict safety and regulatory requirements.

2.4.2. Market Requirements

The success of any product is highly dependent on meeting the market requirements. Therefore, it is essential to understand the customers' needs and preferences, the competitive landscape, and regulatory requirements. To do this we conducted a survey of some of the key companies involved in the H2 ecosystem operating in the UK. This included manufacturer of vehicles, EPC companies, and operators of construction equipment.

The objective of the survey was to gain a comprehensive understanding of the user requirements and prevailing practices for hydrogen applications in the off-road and NRMM (non-road mobile machinery) sector, particularly in the European market. The survey encompassed a range of topics such as hydrogen utilization, retail prices, operational routines, refuelling speeds, and physical limitations. NanoSUN endeavoured to engage with industry leaders in the NRMM domain to gather relevant insights. The NanoSUN Commercial team developed the survey, which consisted of seventeen questions.

The report discusses the results of a survey conducted to understand user requirements for hydrogen applications in the off-road and NRMM sector in the European market. The survey covers performance, cost, environmental impact, compatibility, and legal and regulatory compliance. The report finds that the estimated potential hydrogen consumption across various sites ranges from 100kg/day initially to 50 tonnes/day long term.

It also notes that vehicles around 3 or 4 tonnes are likely to be hydrogen-powered, with a mixture of hydrogen fuel cell vehicles and hydrogen internal combustion engine vehicles. [redacted] and several parties had no reservations on choosing a mobile refuelling solution now, however several parties were considering going straight to fixed hydrogen infrastructure. The report also finds that a range between [redacted] unit was outlined for the cost of a mobile refuelling solution, and there was a consensus that customers and the government want emission-free solutions in the construction industry.

Drawing definitive conclusions from the survey results was made difficult due to the lack of response from many of the companies approached, the lack of confidence in the answers given and the sometimes-conflicting requirements expressed in follow up conversations with the participants and other industry experts. At this stage there remained significant risk in developing the P150 solution and so a Pugh matrix assessment was performed to decide on a solution which would capture the spirit of the information gathered (Ref ANNEX A).

2.4.2.1. Lessons learned as part of this exercise

Surveys may not always be the best tool for market research: If a survey is the only tool being used for market research, it may not capture the full range of market requirements and nuances. Other research methods such as interviews or focus groups may be needed to get a more comprehensive picture.

We should consider alternative ways to encourage participation: as few responses were received, we could consider alternative ways to encourage participation such as incentives or targeted outreach to specific groups. We could have also looked at employing a 3rd party specialist in conducting market research.

The response quality may be a result of not defining the target audience precisely enough. Refining the survey audience to a more specific group could yield better results however we received extremely limited results and so more data would have been a higher priority.

We must ensure the survey questions are clear. Ambiguous or open-ended questions may result in inadequate quality responses. We should have a mix of questions which are clear and unambiguous to receive more useful responses. We could in the future re-evaluate the questions between participants to ensure we are receiving valuable data.

Managing our expectations and keeping them realistic, we understand we operate in a nascent market and so many of our targeted customers do not fully understand what they need. It may be necessary to supplement the survey with additional research or have proposals which we can present to get better quality feedback.

We could have spent more time following up with non-respondents and using personal connections to try and encourage participation. It may also be helpful to identify and address any issues that prevented them from participating so these can feed into further lessons learned.

2.4.3. Technical Requirements

Technical requirement generation is a crucial part of any product development process. It involves identifying and defining the necessary features and characteristics that a product must possess to meet the needs and expectations of its intended users. In the case of the P150 system, the technical requirements were generated through a process that involved leveraging the experience gained from previous product development and consulting with our engineering and manufacturing departments. To begin with, we conducted a thorough review of our previous product development experiences, focusing on the successes and challenges we encountered during those projects. This review helped us to identify the key factors that contributed to the success or failure of those projects. It also provided valuable insights into the technical requirements that were necessary for the development of a successful hydrogen refueller. The use of a lessors learned session allowed open and honest discussion around some of the challenges encountered previously and innovative solutions on how we would address these going forwards.

We then used this knowledge to define the initial set of technical requirements for the P150 hydrogen refueller. These requirements included factors such as the rate of hydrogen delivery, the range of potential hydrogen consumption across different sites, the types of vehicles that the refueller would need to support, the required filling time for the refueller, and the weight and mobility of the refueller. Once we had established these initial technical requirements, we began a process of consultation with our engineering and manufacturing departments. This involved meeting with experts from each department to gather feedback on the initial technical requirements and to identify any additional requirements that had not been considered.

The consultation process was critical in ensuring that all necessary technical requirements were identified and included in the final specification for the P150 hydrogen refueller. It allowed us to tap into the expertise of our entire organisation, including engineers with experience in mechanical design, electrical engineering, and software development, as well as manufacturing specialists who were well-versed in fabrication, assembly, and quality control.

During the consultation process, we also worked closely with our engineering team to develop a detailed functional specification for the P150 hydrogen refueller. This specification outlined the technical requirements in greater detail and the design parameters that would need to be considered, key parameters included, ensuring adequate provision for EC&I components as this had been a major challenge with previous projects, and ensuring that the system would be able operate in a wide range of environments.

As part of the functional specification development, we also identified key performance metrics for the P150 hydrogen refueller. These metrics included factors such as the number of vehicles that could be refuelled, the efficiency of the refuelling process, the safety of the system, and the reliability of the components.

The functional specification was then used as the basis for the concept design of the P150 hydrogen refueller. This involved working closely with our R&D, mechanical design, and manufacturing teams to ensure that the technical requirements were translated into a design that could be feasibly manufactured and assembled.

2.4.3.1. Lessons Learned

We must involve all relevant stakeholders, it is important to involve all relevant stakeholders in the development of technical requirements, including engineering, manufacturing, marketing, sales, and operations. This ensures that all perspectives are considered and that the requirements reflect the needs of the entire organisation.

We did a respectable job of leveraging previous experience by reviewing previous product development experiences we gained valuable insights into what works and what does not when it came to developing the technical requirements. This can help identify potential pitfalls and opportunities for improvement.

We should have started with high-level requirements, if we had begun the process by defining highlevel requirements that reflect the overall goals and objectives for the product, we would have a framework for the development of more detailed requirements.

We could have had a more structured approach, such as the V-model. This ensures that all requirements are properly documented and that there is a clear traceability between requirements and design activities.
Ensure requirements are measurable, as we had a mix of measurable and non-measurable requirements. Technical requirements should be measurable, so that they can be objectively verified and validated. This ensures that the product meets the intended specifications and performs as expected. Where we had less well-defined requirements they should have been rewritten and reconsidered.

We ensured that technical requirements were verified and validated throughout the development process at multiple stages and pulled out the key requirements as KPI's that the design could be measured against. This helped to identify issues early on and ensured that the final product meets the intended specifications.

We failed at revising requirements as new information became available and the project development process had begun. If we had reviewed the requirements in multiple stage gates, we could have ensured that only valid requirements were being carried through the project. While we updated the design as we gathered more detailed information it is not clear what the process was for reviewing the requirements and ensuring they were still relevant.

We could have done better at using feedback from customers and stakeholders. If we had solicited feedback from customers and stakeholders throughout the development process, we could ensure that the product is meeting its intended function. The challenge to this was identified in the market capture exercise where we gained little valuable information.

2.4.4. High Pressure Storage System

Several types of compressed gas cylinders are available for storing hydrogen gas, cylinders are defined according to their construction. For mobile refuelling applications the type of gas storage is one of the key design parameters as it defines the rest of the operating parameters of the system. Type 1 cylinders are made of steel or aluminium, these are heavy, and more suitable for stationary and high-volume industrial use. Type 2 cylinders are aluminium cylinders hoop-wrapped with composite fibre, these are lighter than Type 1. Type 3 cylinders have a composite fully wrapped around an aluminium liner. Type 4 cylinders are made of composite with a polymer liner. The benefits of type 3 and 4 cylinders is seen in their reduced weight and high storage pressures.

Type 1 cylinders are cheaper but significantly heavier than types 3 and 4, for a mobile refueller to be cost effective it must transport large volumes of hydrogen at low cost. Systems made from type 1 cylinders are often restricted by the weight of the system due to limits for road transport, whereas Type 4 cylinders are often prohibitively expensive due to the fact they are still an emerging technology.

	Type 1	Type 2	Type 3	Type 4	Type 5
Liner Material	All metal	Metal	Metal	Plastic	-
Resin type		Thermosetting	Thermosetting	Thermosetting/Thermoplastic	Thermosetting/Thermoplastic
Fibre type		CF/SW(cylinder wrap)	CF/SW(Full wrap)	CF/SW	CF
Winding method	-	wet	Wet	Wet/tape	Tape

Table 1: Cylinder type Manufacturing differences

To assess which cylinders would be used in P150 an extensive search of the market was performed and all cylinders which presented themselves as a reasonable option were collated into a database. The cylinders were then compared on a number of key parameters such as: Maximum pressure, weight, volume, length, width, and cost. This allowed us to calculate the costs in terms of not only stored hydrogen but also in terms of hydrogen delivered through the development of our in-house modelling tools.

The technical requirements made it clear we must be able to refuel heavy duty vehicles to the standards defined by internationally recognised refuelling protocols. Our understanding of the target segment for P150 is that the decision between the two standards of 350 and 700 bar has not fully been decided. This means that for P150 to effectively supply both types of vehicles we need to have storage at high pressure to cascade effectively.

[redacted] Different standards are used to certify cylinders for vehicles and cylinders for distribution. NanoSUN has investigated recertifying vehicle tanks however the burst pressure requirements are lower and so the certification of these tanks would result in storage at a lower pressure than required.

As part of the lessons learned from previous projects, we decided we must have multiple sources for the cylinders, it was also clear from the technical requirements that the cylinders should be lightweight. This left us with two cylinders as an obvious choice, due to their cost, storage pressure and similarity in dimensions, we would be able to design a system which could use cylinders from either supplier. This complicates the design however it also means only a single design would be required for both cylinders and they could be mixed and matched if needed.

There has also been a recent change to the ADR which allows a different standard to be applied when certifying type 4 carbon fibre composite wrapped cylinders. The new standard recognises the safety and behaviour of these cylinders and as such they can now be operated at higher pressures. This development reaffirmed these cylinders as the optimum choice as their price to storage ratio and total storage improved further while maintaining the same cylinder weight, improving the overall performance of P150.

With the gas storage cylinders defined and a defined a space envelope for the P150 system based on the number of gas cylinders that could be transported by a single vehicle we were able to calculate the maximum amount of hydrogen that could be transported by a single system. This was a crucial factor to consider, as the P150 system needed to be mobile and easily transportable to distinct locations.
Through the development of operating models and refinement of simulation software we could also identify potential use cases for different number of cylinders grouped into different numbers of cascade stages. Significant work was performed examining the economic impact to operators by varying the number of cylinders and the volume of cascade stages. Some of the key influencing factors are the types of vehicles being filled, the size and pressure of the receiving tanks, and the [redacted]

[redacted]

[redacted]

[redacted] We will then use our expertise to recommend a system to a customer with the option for them to adjust the system to their needs.

To size the system one of the analyses we performed was a cost-benefit analysis, where we compared the costs of implementing the system against the potential benefits it would provide. We identified the costs associated with the gas dispensing system, including the initial investment in equipment, ongoing maintenance, and operating costs such as delivery, and the cost of the gas itself. These costs were compared against the potential benefits of the system, such as reduced delivery costs, increased efficiency. While not accounted for financially an additional benefit is improved environmental impact.

We also performed a net present value (NPV) analysis to calculate the present value of the future cash flows generated by the gas dispensing system, considering factors such as inflation and the time value of money. This analysis helped to determine what sized system is a financially viable investment over the long-term.

Finally, we conducted a sensitivity analysis to assess the impact of changing variables on the financial viability of the gas dispensing system. This analysis examined the impact of changes in gas prices or delivery costs on the overall ROI or NPV of the system.

In this analysis we had to make assumptions on the operating behaviour of users as there is extremely limited data available on usage patterns due to the lack of widespread adoption, lack of engagement in the survey and the fact the industry is still developing. For the moment we have shortlisted two possible viable cylinder options. Provided that there is no new development in cylinder technology in the next year or so either of these cylinders can be used for our detail design and prototype (see ref [redacted]

2.4.4.1. Lessons Learned

In this phase of the project the key lessons learned were:
When examining the availability of newly developed technology, it is essential to keep an open mind and be receptive to innovative ideas and approaches, this was done well when we examined the options of developing our own cylinders, partnering with cylinder suppliers to develop new products, and examining the possibility of recertifying existing cylinders.

It is important to thoroughly research and understand the technology we are considering. This includes not only the technology itself but also any associated risks, costs, and benefits. It allowed us to make an informed decision between different cylinder, types, sizes, and pressures.
It is important to engage with stakeholders, including end-users, investors, and other key players, to understand their needs and requirements. This allowed us to develop models to predict usage allowing us to perform an economic analysis.

We should evaluate the feasibility of implementation; this includes not only technical feasibility but also financial and operational feasibility. One of the driving factors in the decision-making process was the minimum order quantity and the scope of the suppliers to meet our demand. One aspect of the feasibility we could have improved on was the ability of the cylinder supplier to mount and frame the systems for us which would reduce the engineering and manufacturing time and resource required by NanoSUN.

New technology is constantly evolving, and it is essential to be prepared to adapt and change course if necessary. This may involve revising plans, adjusting timelines, or exploring alternative solutions. With the implementation of new cylinder standards, we did this well adjusting our plans as new cylinders became available.

2.4.5. Preliminary P&ID and BOM Development

The R&D department at NanoSUN worked to develop a concept P&ID for the P150 system, with a particular focus on safety, digital functionality, and user experience.

One of the key considerations during the design process was creating smart gas storage that could protect itself in case of system failure. The team worked to incorporate a range of safety features into the P&ID to minimise the risk and impact of accidents or equipment failure. This included automatic shutoff valves and pressure relief systems that could activate in the event of an emergency. This makes the P150 a safer system than regular MEGC's which rely on the dispensing system to provide necessary protections.

Line sizing involved determining the appropriate size of the pipes and tubing that would be used to transport hydrogen gas throughout the system. The goal was to ensure that the lines were large enough to handle the required flow rate, but not so large that they would be unnecessarily expensive or cumbersome to install. This has been a key lesson learned from our previous products.

To determine the optimal line sizing for the P150 system, the R&D team leveraged a range of simulation and modelling tools using commercially available tools to validate the development of inhouse models. They tested various line sizes and configurations to identify the optimal balance between system performance and difficulty in manufacture and assembly.

One of the key trade-offs involved in line sizing was between system pressure drop and line size. A smaller line size would create a larger pressure drop, which will reduce the overall performance of the system. However, a larger line size requires more material, different components, space for routing, tools for assembly etc.

The team also considered the impact of line sizing on the overall safety of the system. They worked to ensure that the lines were designed to handle the maximum expected pressure and flow rate of the system, however as line sizing is increased the forces on the tube also increase and so standard process tubing may not be adequate. There are solutions to this such as increasing wall thickness, changing material or hardening the tubing, however this can create significant additional cost.

In addition to safety features, we also focused on digital functionality for the P150 system. The system was designed to incorporate real-time monitoring and control systems that could alert operators to potential issues and provide them with the ability to adjust the system as needed. This allowed for greater control and flexibility in the operation of the system.

Another consideration during the design process was the trade-off between including components in the gas storage system versus the gas dispensing system. Some of the key components that impact this decision are [redacted]. Both of which can add significant cost to the system while also introducing unique failure modes and safety challenges. [redacted]

[redacted] This necessitated additional complexity on the gas storage system and a control system, however it also provided an opportunity as it allowed additional functionality and safety systems to be implemented with minimal marginal cost.

This allowed for greater efficiency in the overall operation of the system while also reducing the total cost for most users. [redacted]

Challenges such as these were encountered repeatedly throughout the design process. As the team worked to improve the user experience for the P150 system while avoiding too much additional cost and maintaining strict safety standards. Working closely with process engineers ensures that the design met these standards.

To ensure the P&ID was achievable, the R&D team worked closely with mechanical design to incorporate 3D modelling and simulation tools to design and test different P&ID configurations. This allowed them to quickly identify potential issues and make adjustments as needed. The mechanical model was designed with user-friendly interfaces and intuitive controls, making it easy for operators to understand and use. The team incorporated feedback from potential end-users into the design process, ensuring that the system would meet their needs and preferences.
Ultimately, the engineering team were able to develop a concept P&ID for the P150 system that prioritised safety, digital functionality, and user experience. The resulting design provided a solid foundation for the development and implementation of the P150 system.

With an outline P&ID we were able to then develop the BOM, we first identified the key process components needed for the system. We had already identified cylinders and so this was mainly focused on valves, hoses, connectors and sensors. We then began contacting manufacturers to determine the availability and cost of each component. This involved researching manufacturers online and contacting them via email or phone. In many cases we used outline costs from previous products to provide an initial estimate and then updated these costs as more information became available.

Some manufacturers were more responsive than others, and we found that arranging in-person meetings was often more effective than simply communicating through email or phone. This allowed us to review product catalogues and discuss our specific needs and requirements in greater detail. We had significant interest from some of the major valve manufacturers who are keen to establish a foothold in the hydrogen market.

For some of the more complex systems we submitted preliminary P&IDs to be bid against. This allowed us to compare quotes from different manufacturers and select the most cost-effective option for these systems. It reduces the risk for NanoSUN if multiple components can be supplied by a single manufacturer in an assembled package.

We quickly discovered that the availability of certain components caused some redesign and development of the P&ID. Some components were simply not available in the quantities we needed or were only available at a significantly higher cost than we had anticipated.

In these cases, we had to go back to the drawing board and find alternative solutions to meet our requirements while staying within our budget. This involved redesigning the P&ID to accommodate the new components, and in some cases, even redesigning whole systems to ensure compatibility with the new components. (For full [redacted]

2.4.5.1. Lessons Learned

Effective communication and collaboration are key, The P&ID development phase involved several specialists working together to create a comprehensive diagram of the system. It was crucial to establish clear lines of communication between the different teams to ensure that the concept would be deliverable.

Conflict management should be considered as part of effective communication, in some cases team members disagreed on how certain design features could be implemented and it was important to reach a consensus in order to progress.

For the above reason individual team members must be flexible. The P&ID development phase involved multiple iterations and revisions as new information became available or as changes were made to the system design. It was important to remain flexible and open to making changes as needed to ensure that the system would meet its design requirements.

P&ID design requires high attention to detail, as the design is reviewed by different departments mistakes or errors in the P&ID can lead people to draw incorrect conclusions and sign off on designs which are not to the intent of the system.

When operating in developing industries with new technology it is important to understand the availability of components. In many cases a valve or component was specified where none were available or if they were the cost of implementation was prohibitive. In future projects the procurement team should be involved to examine design intent and provide feedback on whether a design is feasible from a supply chains perspective.

2.4.6. Conceptual 3D Model

Using 3D modelling tools, the mechanical design team was able to create a representation of the P&ID. This allowed us to see the system in a way that was not possible with 2D drawings and diagrams created in the early concept development phase. By visualising the system in 3D, we were able to identify potential design issues and address them early in the concept phase. One of the key benefits of identifying issues in the concept phase is that it allows the team to refine the design early on, before significant resources have been committed to the project. This means that changes can be made relatively quickly and inexpensively, without causing significant delays or additional costs. [redacted] ould fit in this space enveloping using a range of arrangements. The varying arrangements however caused downstream complexity in the manufacturing process which was identified during the DFX process. DFX (Design for X) is a systematic approach to product design that focuses on optimizing various aspects of the product's design, with the goal of improving its quality, reliability, manufacturability, and overall performance. With this challenge highlighted it was decided to review the product requirements and decide which requirement was a higher priority [redacted]

To ensure that we were exploring a range of viable options, we had engineers developing parallel concepts. This allowed us to compare and contrast different design options and choose the best one based on a combination of factors, such as manufacturability, cost, and performance. Creating parallel concepts also helped to mitigate the risks associated with any one concept failing. By having multiple concepts in development, we were able to shift resources to the most promising concepts if one of them proved to be unfeasible.

As a mobile refueller seeks to maximise the quantity of H2 transported the available space for process and EC&I equipment ends up being minimised. The 3D model allowed us to critically examine the space available and the space requirements for this equipment. It also highlighted issues we had made due to assumptions on the control system; where the location intended for its installation was unsuitable due to ventilation requirements. This conflict highlighted the need for EC&I to be involved in the mechanical design process where possible to ensure their interests are looked after.

It also highlighted the competing requirements of different requirements established in the earlier phases of the project. Prioritising the amount of fuel on board minimises the space for other components, which leads to complexity in design, difficulty in manufacturability and risks to the supply chain if the space envelopes become too tight. All of this drives up the capital cost of a refuelling system. If we instead prioritise the manufacturability of a system, we sacrifice much of the gas storage and deliver a system which costs less up front but has a higher operating cost as it must be refilled more often. To make an informed decision we analysed how, the asset cost and the expected lifetime operating costs changed with the number of cylinders in a system. This was compared to manufacturing and assembly cost in terms of hours so it could be understood if making the assembly more expensive would be of net benefit to the operator of the system.

We also solicited feedback from our commercial department and potential customers who informed us that in many cases increased costs up front could actually be beneficial due to incentives around developing their hydrogen systems.

Initial concepts of the system also addressed the complexity of having a system which can be operated in multiple configurations. It was designed so that it could be operated on the ground or mounted on a trailer. This required the user interface to be mobile in addition to the fuel delivery hoses.

Overall, the development of 3D models provided useful as it allowed thorough discussion of the design requirements. Allowed us to visualise the system and consider how it would be operated. It also provided a framework for showing the concept to the wider business and our partners in a way that technical drawings and documents cannot (ref ANNEX D/ Concept design Modles.ppt).

2.4.6.1. Lessons Learned

The use of 3D modelling tools allowed us to create a detailed and accurate representation of the P&ID, which helped us to better visualise and understand the design. This allowed us to identify potential issues and make informed decisions about the design.

The 3D concept model allowed for better collaboration between different teams and stakeholders involved in the design process. By visualising the design in 3D, it was easier to communicate design concepts and ideas to others, allowing for more effective collaboration and decision making.

By developing multiple parallel concept models, we were able to compare and contrast different design options and identify the optimal design solution. This allowed us to optimise the design for factors such as manufacturability, assembly, and serviceability, resulting in a better overall product. This however has a cost, it may have been better to co-locate the designers and have them discuss design options in real-time, this would have accelerated the design phase, but it may have caused us to reach a local maximum if a wide range of options cannot be fully explored.

The 3D concept model allowed us to identify potential issues with the design early on in the process, which helped to minimize the risk of costly design changes later in the development process. This allowed us to make informed decisions about the design and ensure that it met the requirements of all stakeholders.

The Models have also shown that we can develop a design that can be modularly increased in size and capacity over a minimum viable threshold. This means we can have a few [redacted]

Technical requirements must be reviewed, the 3D model highlighted conflicts in the technical requirements and so time should be taken to manage conflicting requirements, and, in many cases, an in-depth analysis may be required to determine which requirements supersede others.

2.5. Investigation and Testing

2.5.1. Introduction

The NanoSUN wanting to take advantage of the fact that we already had a road going functional product decided to conduct S&V testing on 5 key system panels of the P145 unit. The intent was to simulate the effects of the unit moving off-road and identify structural weaknesses and future failure concerns. This would give us insight into the effects of the vibrations and help us add these as lesson learnt and requirements for the eventual P150 design phase.

Details of the testing performed for shock and vibration are contained in deliverable NAN0102, dated 23rd February 2023. Further details of the pressure testing performed as assurance of the S&V testing is contained in deliverables PT-SO1149. Design recommendations and future work items for off-road optimisation have been extracted from the testing and recorded in NanoSUN internal issues tracking database.

2.5.2. Shock & Vibrational Testing Pre work

Shock and vibrational testing of existing Pioneer 145 technology was identified to understand behaviour of the design when exposed to an environment akin to that experienced when the system is transported off-road, for example in a construction or mining use case.

Due to complexity and spatial constraints the entire system was not a credible candidate for this test regime. Therefore, significant equipment and components, designed and manufactured as panel-based assemblies, were selected. This includes all electrical components and instruments used on the Pioneer 145 system and all variants of breakable mechanical connections that may be susceptible to leakage.

2.5.2.1. Design

[redacted] gas panel assemblies were proposed for design and development, to cover all gas transfer scenarios the Pioneer 145 system would experience during off-road use: transfer between cylinders, refuelling, filling and venting. The designs utilized existing Pioneer 145 components and followed the identical design process as used by NanoSUN Quality Process 04. The designs were created by Mechanical Design Engineering, checked by Systems Engineering team then approved by the Chief Engineer.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

2.5.2.2. Procurement

During the procurement phase it was important to maintain existing suppliers and processes as far as possible to replicate the methods used during Pioneer 145 production. All components used were required to be supplied with an overall Certificate of Conformity and meet the requirements of the EU Pressure Equipment Directive (2014) for pressurised equipment, which includes requirements for material traceability and test records. All other functional requirements were brought across from similar production Pioneer 145 systems.

[redacted] were used to manufacture these [redacted] assemblies. They are an established fabricator and panel builder for NanoSUN and had experience with our supply chain and technical contractual requirements. The Request for Quotation process took longer than expected as there was an ambition to use [redacted] own procurement team to directly source our Bill of Materials for efficiency purposes and to trial a new sub-process, however upon comparison of the two approaches it was found that the existing NanoSUN method of purchasing and free issuing our stock was advantageous. This project was a valuable opportunity to compare the two processes.

A noteworthy issue was discovered where [redacted] were performing their own ‘goods in’ of our component kits and finding parts missing from the drawing list. This was traced back to a root cause in the NanoSUN logistics team and provided a process improvement for how we manage and release stock kits.

2.5.2.3. Manufacture

[redacted] were able to use existing staff, tooling and procedures for assembling and acceptance testing (FAT), with successful results which both proved our existing manufacturing processes we had agreed with them but also assured that the assemblies being sent for testing were of ‘production ready’ standard.

A significant manufacturing time improvement was discovered in the RDR project plan for WP3 due to [redacted] applying internal lessons learned from earlier Pioneer 145 panel builds. This allowed recovery of the overall project delivery in Q4 2022 to support testing in Q1 2023.

The manufacturing phase concluded with pneumatic pressure testing at a sub-contracted test house, [redacted] to 1.1 times maximum rated working pressure. This is the same process step as followed for similar production units and is the final hold point in the manufacturing plan.

Due to [redacted] being in close proximity to the final shock and vibration test house we were able to ask them to perform this test to assure the manufacture and the pre-vibration state concurrently. This was important as any leaks found post vibration needed to be directly attributable to the shock and vibration profiles as opposed to any doubt being present as to the pre-test condition.

2.5.3. S&V Testing

Two test houses tendered for the shock and vibration scope of work, [redacted]. Both proposed using Def Stan 00-35 Environmental Handbook for Defence Materiel based vibration profiles and shock criteria. This was accepted as the criteria was applicable to a wide variety of assembly and equipment types and did not require existing data on applicable samples to calibrate the testing, which is the case with the majority of commercially available standards.

Both bids were technically and financially competitive and were suitable for selection in the view of the technical lead on the project. [redacted]

The technical requirements for the scope of work were issued in the Gas Panel Test Specification [redacted] and are summarised as:

- Vibrational testing to represent profile for equivalent 1000 kilometres of off-road travel, in accordance with Def Stan 00-35 Part 4, module A2 or A4.
- Shock profile as per Def Stan 00-35 Chapter 2-03 A3a, at least 20g force per axis.
- Mount samples using identical fixings and fasteners to test house made fixtures.
- NanoSUN to conduct pre and post pressure testing to 1.1x maximum working pressure to validate as built leak tightness and as shocked/vibrated leak tightness.
- Run samples for the lesser of 1 hour duration per axis for vibration testing, or until destruction.

Results and observations of the testing are contained in [redacted] supplied *Vibration and Shock Testing of Gas Panels NAN0102* and summarised below.

[redacted]

The assembly suffered a failure of the fixings [redacted] This occurred [redacted] minutes into the lateral axis vibration testing, having successfully completed its shock test and other 2 axis vibrations. It is apparent upon inspection that the nuts welded to the back of the mounting plate to secure the fastenings may have lost integrity of the weld due to the testing. For this design it is proposed to; [redacted]

[redacted]

The assembly suffered a failure of the fixings [redacted]. This occurred [redacted] minutes into the longitudinal axis vibration testing, having successfully completed its shock test and other 2 axis vibrations. It is apparent upon inspection that [redacted]

[redacted] This has reinforced the need to change the number and position of fasteners being used in this application as part of the corrective actions from the [redacted]

[redacted]

The assembly suffered a pressure gauge failure whilst being vibrated after 26 minutes in the lateral direction, this manifested as the external and internal casing becoming loose from the pressurised section. This was not a safety risk in terms of releasing pressurised gas but did render the gauge inoperable.
One other superficial failure was noted which was the loosening of the rubber plates used to support the high-pressure coupling.

A design recommendation arising from this test was to change the bonding agent used to secure the rubber. A maintenance recommendation has been transferred to the operator manuals to check and ensure integrity of pressure gauges at regular intervals for the systems when used in off-road environment.

[redacted]

On this [redacted] assembly, the [redacted] It has been taken as a design improvement to review the rubber type being used for these mounts and implement a stiffer construction that does not apply the amplitude of movement when exposed to this type of vibration level.

No components were permanently altered in position or experienced excess displacement upon inspection from a strobe light-based frequency sweep, an extra analysis used for this fixture due to the amount and complexity of the components fitted.

No significant failures were observed during the test. [redacted]

[redacted]

A strobe light search was also conducted on this assembly and confirmed no excess displacement of components took place during the vibration testing. There were no failures or observations made on this assembly as a result of shock or vibration testing.

2.5.3.1. Test result

The assemblies were dispatched back to [redacted] for final pneumatic pressure testing (reports [redacted] to validate condition following shock and vibrational testing. It was decided not to conduct this on 73-ISO-002 and 73-ISO-003 (manifold panels) due to the [redacted] taking the assemblies out of design intent boundaries.

For [redacted] The two-stage pressure test was successful to 1.1x maximum working pressure.

For [redacted] the three-stage pressure testing was all successful to 1.1x maximum working pressure.

For [redacted] the pressure testing was successful to 1.1x maximum working pressure.

NanoSUN have taken design and maintenance improvements for [redacted] assemblies tested. It is acknowledged that the electronic behaviour of the instruments and equipment fitted to the assemblies has not been proven in a production use case since shock and vibrational testing and as such the testing to date covers mechanical and visual criteria. However, the panels are still owned and held by NanoSUN and have been quarantined for research purposes to explore electrical status at a later date.

It is a particular success that all assemblies pressure tested passed as this was accepted to be a technical risk from early in the project and it was expected that some leakage may occur that would ordinarily require maintenance or a complete replacement of components.

NanoSUN have also achieved a successful and productive working relationship with both [redacted] for future research and testing purposes.

2.5.4. Proposed Design Improvements

Following on from the findings of the S&V testing NanoSUN have taken design and maintenance improvements for [redacted] assemblies tested.

Assemblies [redacted] suffered identical failure of the fixings [redacted]

For assembly, [redacted] preventative design recommendation from the test results was to change [redacted]. The recommendation is an increased maintenance action which has been transferred to the operator manuals to check and ensure [redacted] for the systems when used in off-road environment.

On the [redacted] the design improvement takeaway is to review the [redacted]. The sourcing of an alternative [redacted] will take place outside the scope of this project.

In addition, the more straightforward design improvements/maintenance measures would be to:

[redacted]

2.6. General Project Lessons Learned

The lessons learned for the P150 preliminary design, and the shock and vibrational testing sections of the project are detailed in section 2.

Two key lessons learnt outside of those two sections are:

1. The construction space does not really know what it needs when it comes to adopting hydrogen gas a fuel to replace red diesel. Comparable costs to the diesel model were expectedly favoured, a mobile solution was repeatedly requested, and a refuelling system needed to be remotely powered. However, critical details regarding how much hydrogen is need on site per day and the types of vehicles that needed to be refuelled were not clearly outlined known.

   The market research does show that immediate pull for a hydrogen transition lies with the construction industry as that is where the most government incentives are. But the market is in early test and development stages of H2 vehicle prototypes and hence the operational requirements for a refueller are not well known.

2. Upon investigation of cylinder suppliers and regulatory standards of transporting hydrogen gas we had incorrectly believed there was a 500 barg pressure limit within Europe. From investigations with our cylinder suppliers and reviewing the relevant standards (ADR and TPED) it was discovered that there was no maximum pressure limit on transporting hydrogen gas on the roads in Europe. This is significant as it allows the Pioneer150 to base its design on cylinders greater than 500 barg which will allow the refueller to store more hydrogen on board and refuel more vehicles, decreasing downtime and operational cost.

2.6.1. Project Management Lessons Learnt

ID	LESSON LEARNED	BUSINESS AREA	WHAT COULD HAVE BEEN DONE BETTER?
1.	A Procurement Plan should have been set up prior to Procurement stage of Project	Project Management/Procurement	This should have been set up in advance of the Procurement stage of the Project
2.	A Test Schedule should have been received from Test Houses	Project Management	NanoSUN did ask several times for these, but it should have been escalated to Management at [redacted]
3.	Cost to Complete should have been identified at start of Project.	Project Management/Financial	At Project Kick Off a design to cost figure should have been identified and monitored during Project
4.	More regular review of Project risks/issues	Project Management	Risks/issues should have been reviewed on a weekly basis

5.	Too much reliance on a single resource within Engineering to provide technical direction.	Engineering	Lead Engineer should have delegated tasks into wider Engineering Team
6.	Taking less time to choose appropriate test house	Project Management/Engineering	This decision could have been made quicker
7.	More frequent meetings with the customer	Project Management	Meetings were monthly but they should have been more frequent (i.e., every 2 weeks)
8.	We should have ensured positive confirmation of all parts received from Suppliers	Procurement	Set up a meeting with Supplier once BOM received to ensure all parts received.
9.	A number of part numbers were incorrectly recorded on the BOM. Concessions had to be raised and this added complexity	Procurement	Dedicated ME resource required (support)
10.	Sub-contracting pressure testing earlier	Operations	Identifying suitable sub-contractor earlier to take pressure off operations team
11.	Simplifying design scope with Mechanical Design Team to achieve similar benefits in much shorter time scale	Engineering	More regular communication with Mechanical Design Team so that they fully understood the scope of the task.
12.	Including R&D in Project updates to ensure alignment with WP2	R&D	Inclusion in regular meetings and communications.
13.	Earlier delivery of test spec to test house	Engineering	Delivery of test spec with RFQ to ensure better understanding of scope with test house.

2.7. Preliminary design Summary

The work carried out in this project has allowed NanoSUN to progress with the following:

- Recognising the needs of the construction/NRMM sectors when thinking about a transition away from diesel to hydrogen.
- Generating a global view of the available high pressure hydrogen storage cylinders available in the market.

- Identify several suitable high pressure hydrogen storage cylinders for the next generation of Pioneer stations.
- Progressing through the preliminary design review stages creating an initial P&ID, BoM & 3D Model for a Pioneer station catered for NRMM applications.
- Conducting shock and vibrational testing on the Pioneer gas panel to understand the mechanical robustness of the design for off-road environments.
- Producing a high-level timeline and cost plan to develop a prototype of the Pioneer for NRMM applications to carry forward in Phase 2.

The points mentioned above have allowed NanoSUN to make a significant step forward in bringing a mobile hydrogen refuelling station for the construction sector to market. NanoSUN have been able to validate the mechanical robustness of the gas panels design with no major concerns that would generate a significant design change. By identifying a suitable high pressure hydrogen storage cylinder as well as, the central part of the design, allowed the development of the entire system. Without this centre piece it would have been difficult to progress the design piece smoothly.

It is difficult to say with certainty but from the preliminary design review, developing a Pioneer for the construction space is possible whilst retaining the Pioneer UPS and traits which make it appealing for this industry. By remaining low cost and mobile whilst combining the fuel storage, transportation, and dispensing functionality, when partnered with hydrogen production and compression players, the Pioneer can provide a full hydrogen well to use operation with end use prices competitive to diesel.

Through the Preliminary design phase NanoSUN has been able to draft preliminary product parameters. Although these parameters are subject to changes and revisions as we go through a detailed design phase. It starts to give structure to the product concept and direct for the detailed design phase. Below are some key design features we believe the product should be based on. For further details refer to ANNEX.E/ [redacted] Product Data Sheet.

• The hydrogen storage system [redacted]

• Each gas bank will contain [redacted]

[redacted]

[redacted]

• [redacted]

[redacted]

In summary, before undertaking this project, the current Pioneer design had been prototyped for on road use and on road hydrogen applications. This project has allowed NanoSUN to make valuable progress in using our knowledge base of the current Pioneer and building blueprints specifically for offroad environments and for NRMM applications.

3. Project phase II

3.1. Project scope

Decarbonisation of the construction industry is a significant challenge. By the fluid nature of how the industry operates permanent energy infrastructure is not viable in the majority of circumstances for the industry. Hence why the sector transport fuels to sites as opposed to going to fuel sources. Compressed hydrogen gas is by far the most efficient carbon-free fuel compared to the current practice of diesel consumption. NanoSUN's innovative combined distribution & refuelling solution achieves the same simplicity with a compressed gas, without the need for high-cost infrastructure. Now it's just a matter of tailoring this solution with the construction industry needs.

Phase 1 of this project has given us a preliminary product concept to work with. Taking advantage of new technology in form of carbon fibre tubing and lesson learned from the design and investigation process we can now work towards designing and building a robust off-road solution with a smaller weight [redacted]) and footprint, suitable for off-road trailers. designed for daily use, with minimal deployment effort.

The next step for this product will be to utilise all the data and lesson learnt gather during phase 1 and carry out a detailed design phase to draft a prototype design. Following the draft of the design we will proceed with building a prototype unit and running rigorous tests and demonstration runs. Engaging with potential customers for feedback and reviews which we can feed back into the design to have a final product version ready for production.

The estimated cost needed for this project and an approximate plan for how we intend to execute said project are shared below.

3.2. Cost estimation

As part of the P150 preliminary design review, NanoSUN have been able to produce a cost estimate for the development of 1x Prototype. This is based on a system which will be [redacted] barg working pressure and hold a capacity of [redacted] kg of hydrogen.

There are several assumptions for this cost analysis i.e., which cylinder supplier is used, labour rates and several estimates for certain components and sub-assemblies. Nonetheless, this provides a solid framework for the expected cost for developing this solution. See breakdown of the costed plan for building and testing a P150 prototype in the table below.

In summary the total project development cost for a P150 prototype comes in at [redacted] to build, test and commission a single unit with the new design.

3.3. Proposed Project Plan

[redacted] proposed lean project plan can be seen below. Based on an October 2023 start date, it is estimated a full 12 months from project kick-off to design, build and test a P150 prototype. At this stage, this proposed plan does not have much contingency built in, hence it would be practical to add a minimum of 3 months extra for slack bringing it to January 2025 for completion.

A commercialisation plan post prototyping has not been developed yet.

The development of the P150 solution is dependent on whether NanoSUN can secure further funding to progress this development. [redacted] NanoSUN have gained valuable insight from Phase 1 that has provided solid foundation to progress the design for this sector and will be looking for future avenues to continue including RDR Phase 2.

4. Route to Market Assessment

NanoSUN's intention for the funding in Phase 1 was to develop the current Pioneer 145 design making it a more suitable technology for off-road applications (i.e., construction NRMM). The preliminary design of the "P150 off-road" provides a functionally more powerful mobile refueller that can refuel more hydrogen NRMM applications than the current P145 design.

The shock and vibrational testing conducted on the gas panels of the Pioneer provided a substantial insight into how a mobile refueller will fare when being transported across off-road conditions.

The findings from Phase 1 will be compiled and distributed outside of this Project into the continued design of the P150 -off road (the name may differ) as NanoSUN see the construction space as a key market for hydrogen. NanoSUN are aiming to apply for Phase 2 funding, however not as a lead but as part of a consortium led by an OEM or a Tier 1/Plant Hire Organisation.

NanoSUN do not intend to be a singular lead for Phase 2 nor the lead project member as the aim is to demonstrate a full end to end solution of the hydrogen supply chain for a hydrogen application in the construction space. NanoSUN's equipment offering is a piece of that jigsaw. The hydrogen production, compression, logistics, site deployment and end user application are not in NanoSUN's remit. After being involved in several matchmaking events and round tables for Phase 2, we have engaged with more suitable organisations who have the intention of leading Phase 2 applications and have stronger connections within the construction sector to pull together a full supply chain.

Furthermore, NanoSUN as an SME, does not have the resource capability or expertise to put together a project of this scale in full, nor to manage or execute it from end-to-end. Hence the reason for not wanting to be the lead project member but a significant partner as a consortium.

If NanoSUN are successful in becoming a part of a Phase 2 consortium this will fund the continued development of NanoSUN's mobile refueller design for the construction sector. Without funding NanoSUN will not be able to progress this development from private funds and if not successful will Phase 2 will be looking at other funding bodies such as Innovate UK.

Following the timeline of Phase 2, the development of a prototype product to market will take the majority of 2024 with deployment opportunities in 2025. Commercial realisation of the product for 2026 and 2027.

Two critical risks for commercialisation are the following:

- The construction industry prioritises another low carbon fuel source to replace diesel instead of hydrogen.
- Another mobile refueller technologies from competitors come into the UK market.

The former, as of today is low risk, as hydrogen is likely to remain a key fuel for the construction industry transitioning away from diesel. However, based on where the industry is as off 2022/2023, the availability of hydrogen must increase and the price per kg must come down.

This is expected in the next 2 years as more large scale, high pressure, green hydrogen sources are coming online across various parts of the UK i.e., South Wales, Glasgow, Aberdeen, West Midlands and the Northeast. With increased availability the price of hydrogen at the gate is expected to decrease significantly. With more hydrogen sources, the logistics service for transporting it to where it is needed may also decrease.

Looking longer term, there is an ambitious strategy from the UK Government to have 10GW of low carbon hydrogen production up and running by 2030 which is encouraging.

The latter risk is high as it is known that competition is growing, and several organisations have the intention of developing a mobile refueller for the construction space.

NanoSUN's development of an existing mobile refueller design for this space could be prototyped by the end of 2024 at the earliest with the assistance of grant funding. This relatively early entry point for the industry de-risks this element significantly but does not remove it and is dependent on how fast other competitor's progress and whether NanoSUN can successfully secure further grant funding.

5. Project Closure Summary

In summary, the Red Diesel Replacement Project that NanoSUN has carried out within Phase 1 has been successful in executing on the desired deliverables.

By manufacturing five gas panels and putting them through shock and vibrational testing under the Def Stan 00-35 Environmental Handbook standard illustrating the structural strengths and weaknesses in our gas panel manifolds that are expected to hold high pressure hydrogen post transport. This was an extremely valuable test for NanoSUN to carry out as the impact on design will improve the safety of the Pioneer product and decrease downtime due to leaks post transit. These are two critical USPs of the Pioneer product and the latter is essential to improve a sluggish industry inundated with hydrogen stations being inaccessible due to unplanned maintenance.

By undergoing this test NanoSUN has gained insight into where design improvements can be made on the gas panels to ensure the product can remain leak free when navigating off-road terrain.

The technological challenge to design a Pioneer suited for off-road environments and NRMM refuelling has been somewhat addressed with this project. By completing the P150 up to a preliminary design, NanoSUN has made significant progress towards developing a mobile hydrogen refuelling station for the NRMM market. The P150 provides a critical part of hydrogen supply chain which is currently not well established, cost effective or quick to deploy. It provides industries which are moving away from red diesel a chance to adopt hydrogen gas for their equipment and scale up their fleets over time without investing in expensive fixed hydrogen infrastructure that may never achieve a reasonable return on investment with minimal fleet sizes. With the Pioneer solution ideally placed to help industries transition away from red diesel to hydrogen,

This project was not without its troubles and hence learnings. There were several aspects of the project management of this project that were challenging, mainly procuring parts from suppliers and limited resource internally to drive deliverables forward. Even though there were some delays in significant milestones (such as the design of the panels), the project was still able to close in time due to the contingency built into the original project plan alleviating the delays. Furthermore, the estimated times for receipt of parts, manufacture of panels and testing were shorter in timescale than planned to balance out the delays.

With the preliminary design of the P150 off-road completed, NanoSUN are one step closer to entering the construction market with a mobile hydrogen refuelling station. The development of the design and the building of a prototype to trial in the market will continue outside of this project and NanoSUN will be looking to enter into Phase 2 of the competition to continue this work.

Contributors/Reviewers

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6. Annex

6.1. Annex A

6.2. Annex B

6.3. Annex C

6.4. Annex D

6.5. Annex E