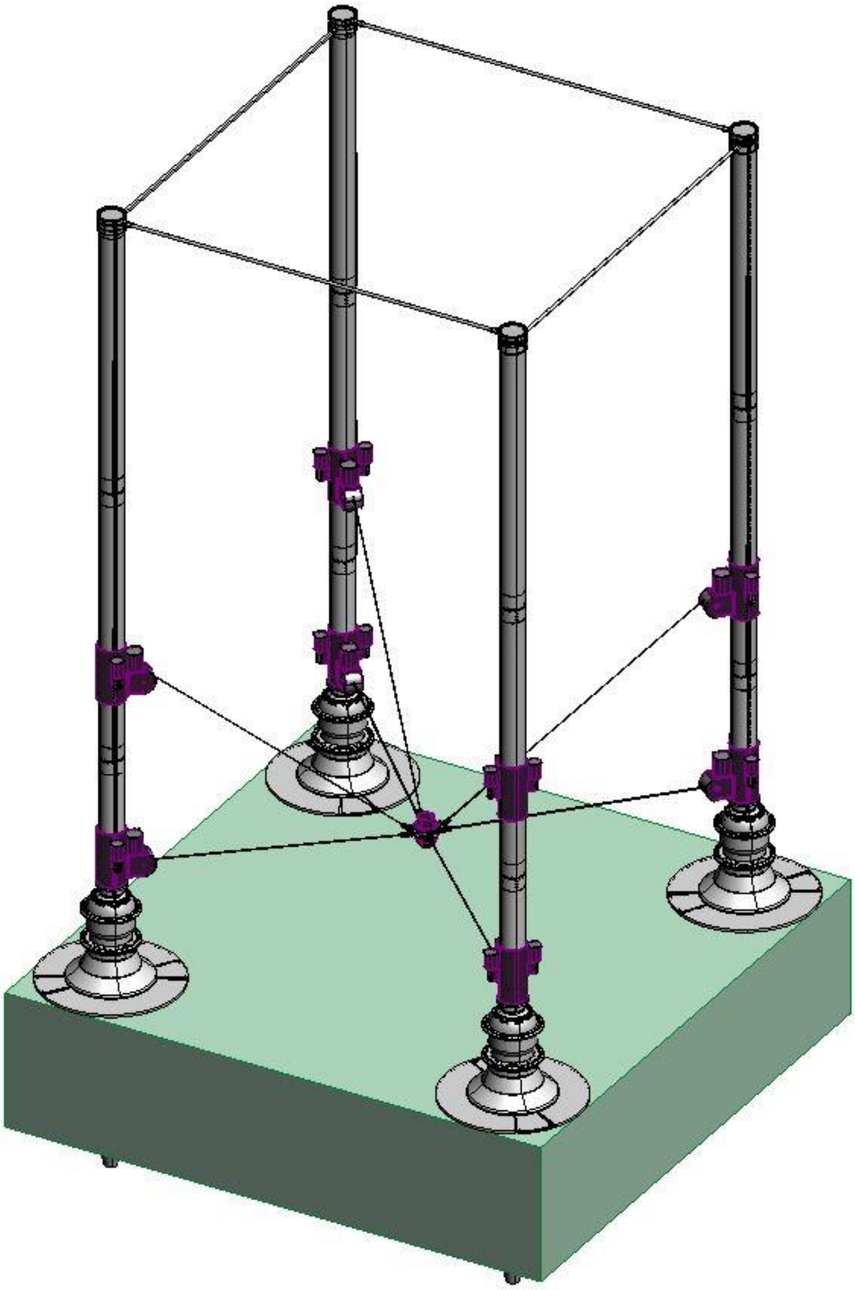
2019



SALEM Printer

Suspended Additive Layer Extrusion Machine

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Abstract

A Proposal for a Construction 3D Printing concept that utilizes cable driven, cartesian movement of an Extruder to produce large, complex cement structures. Includes an analysis of the viability of generating Vertical Farms and a permanent Mars base through the utilization of the SALEM 3D Printing concept.

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Proposal

1.0.0 Introduction

200 years ago, there were approximately 1 billion humans living on planet Earth; Today, we exceed 7.5 billion [1], an impressive rate of growth seen at no other time in recorded history. This explosion in population is ultimately owed to the unfathomable rate at which our technological advantage has progressed over the last century. We have built endlessly on the foundations our grandparents laid, curiosity has led us to the stars and beyond, to the atom and the computer. We have unearthed the mysteries of disease and biological life and have reached the bottom of the ocean only to discover entire alien worlds right under our noses. We've brought all the knowledge of humanity to our fingertips and disintegrated the burdens of distance.

Quality of life today undoubtedly far out paces that of the not too distant past thanks to our innovative nature and lust for a better future, but each problem we solve comes with a price that is often insidious and concealed, quietly compounding over time. In many ways, technology has set us free. But in all too many others, it has enslaved us. We have been lured into a trap of convenience over sustainability, leading time and time again to a path of uncertainty for the future.

None-the-less, we are a species of explorers, innovators, pioneers and tinkerers. From the moment we began using tools we began on an unstoppable trajectory to something more: Something better. However, with a population expected to reach 10 billion by 2050 [2] it is more important than ever to address deficiencies and hazards honestly and urgently and build contingencies that protect humanity from the most imminent threats, because we have advanced our capability for growth, but in doing so have also generated grander ways to bring those imminent threats into realisation.

Climate change is perhaps the defining challenge of the 21st century and is not determined by a single factor, but rather our actions in general. It is becoming ever clearer that to maintain our existence on Earth as we know it, a step evolution in efficiency is required across many functions including; housing, energy production, waste management and agriculture.

In this proposal we discuss the Construction 3D Printing (C3DP) technology concept *SALEM*, that will address a few of these threats and open a pathway to a more sustainable future. We will discuss the form and function of the proposed design and analyse two significant applications unique to this C3DP concept. We will show that it is not only feasible, but highly profitable to build Vertical Farms using this printer, making it possible to reduce our agricultural footprint by up to 98%, potentially allowing over 1.5 billion hectares of land (~36% of all arable land on earth [3]) to be repurposed for growth, or reclaimed by nature.

We will also provide an analysis on how we could establish a permanent 2000-person capacity base on Mars using the SALEM C3DP concept with a team of just 20 people over the course of 1 Mars year. The Proposal will provide an overview of how the SALEM Printer may be developed in practical, tangible terms, offering an approximation of cost, timescales, experiments and associated risks as well as the benefits and expected return rates for the two applications discussed. As part of this programme management plan, we show how the SALEM Printer could be developed in four distinct stages of increasing cost and reward to ensure that financial risk is controlled, and technological progress is structured.

1.1.0 Construction 3D Printing

Fig 1: Apis Cor

1.1.1 Introduction

Construction 3D Printing (C3DP) refers to the process of constructing all or part of a permanent three-dimensional structure automatically and is sometimes referred to as Freeform Construction (FC) or Large-Scale Additive Manufacturing (LSAM). The most typical form of C3DP is extruded additive layer manufacturing. By printing a building in a series of additive layers it is possible to create extremely complex, intricate structures in any form the imagination can conjure. It allows architecture that, for instance, utilises rainwater to feed plants that are integrated into the building design or that generates electricity by redirecting wind through channels in the structure to turbines. [4]

As a concept C3DP is fairly established with the first design proposals emerging in the late 50's and first prototypes following in the 80's, but as a technology it is still very much emergent, for example, the first residential house to be constructed in Europe wasn't completed until December 2017. The outputs so far have for the most part been relatively small-scale and low-volume. As of the start of 2018, fewer than 40 large-scale demonstration projects and prototypes had been fully realized around the world, and the total value of all outputs is estimated at less than $100 million (in an industry with annual revenue of $11.4 trillion globally [5]). None-the-less, C3DP is set to be an astonishingly disruptive technology in the construction industry when it reaches commercial maturity. This is thanks to a range of benefits over traditional construction methods, including reducing the construction time of entire houses to hours [6] and, as there are fewer human resource requirements and the printer uses primary materials to print, the cost of printing a structure using C3DP can be reduced by up to a factor of 10 compared to traditional bricklaying.

The major limiting factor with C3DP is the size of the structures that can be built using this construction method. In most cases, printing a larger structure means building a larger printer, which can quickly become cost prohibitive and impractical as building size is increased. If this restriction is overcome, then the cost and time savings coupled with greater design control and accuracy gained from this technology will drive a revolution in how we construct the cities of tomorrow. Building a permanent structure would become so cheap and easy that all would be able to afford to construct their own dream home and the design freedom that C3DP allows will drive evermore unique and ingenious structures to be built.

1.1.2 Competitor Designs

Although there are a number of printers currently being developed around the world, construction printing is still relatively new in terms of practical application with the first Construction 3D Printed (C3DP) demonstration structures printed in 2006. The largest challenge C3DP Companies face is scalability boundaries with the technology due to the nature of construction projects. As of 2018 the largest C3DP in the world had a print envelope of 7m x 7m x 12m (WASPs "Big Delta"). There are many different general designs of C3DP printers for various applications. Generally, C3DP designs for building cement or concrete structures can be grouped into 4 different varieties:

Rotary Arm Printers

Fig 2: Apis Cor

Rotary Arm printers utilise an arm attached to a fixed central position to print 3D structures around themselves. The most famous manufacturer of this C3DP variant is Apis Cor who was able to demonstrate the capability to print an entire house within 24 hours for under $10,000. The printer can print up to a width of 8.5 meters [7]

Pros and Cons:

The key benefits of this type of printing are the speed of set-up and print. Apis Cor boast a set-up time of just 30 minutes making it great for printing small structures fast. It is also compact enough to ship using standard heavy vehicles, so it is possible to transport the printer to anywhere accessible by truck.

The Apis Cor 3D Printer has a reach of up to 8.5 meters and ultimately depends on the max extension length that can be practically designed into the printer. To overcome the issue of reach Apis Cor have developed the capability to move the printer and continue the print. In practical terms this severely limits the print speed for prints wider than the printer arm length. This type of printer is craned in and out of position meaning that it is also less practical to use this style for multi-storey applications. The package weight of these printer ranges from 2 ton (Apis Cor) to upwards of 15 ton meaning that in order to print more than one floor high, overhead cranes are required to lift the printer up to the next floor and out of a completed floor. This adds time to the print and restricts accessibility due to the fact overhead cranage is required to reposition the printer.

Overhead Crane Printers

Fig 3: Contour Crafting

This type of printer uses an overhead crane to either deposit cement or place bricks and other construction materials. The print envelope is defined by the size of the overhead crane and will typically have one or more fixed axis. Current concepts of this type include traditional Cartesian style Printers such as Contour Crafting (top) and WASPs Big Delta “Magna” (right) that uses the Delta printing concept and achieves movement to specified coordinates by moving each of its three arms independently to one another.

Fig 4: Big Delta

Pros and Cons:

Overhead crane printers tend to be more cumbersome than other C3DP concepts as they require the printer structure to sit around the print envelope and not within it. This generally translates to a higher printer weight and the need for ancillary crane-age to erect the printer.

Once setup is complete, this C3DP variant can print full structures without the need for secondary setup or movement of the printer reducing actual print time.

Modular Printers

Fig 5: WinSun

Some Construction 3D printing companies have tackled the scalability problem by manufacturing buildings in parts at factories then assembling those parts on site. A Chinese company called WinSun are arguably leading the way in this type of printing after making the news in 2014 by erecting 10 full sized single storey homes in a day. Since then, WinSun has successfully printed a five-story apartment block and a 12,000-square-foot (1,100-square-meter) villa, not to mention the Dubai Future Foundation office building.

Pros and Cons:
The main advantage of this type of printing method is rapid final assembly of the printed segments. The time to produce each segment is divorced from the final on site construction, meaning that standard segments can be manufactured and stockpiled ahead of request.

As segments are manufactured off site, final construction requires transportation which, depending on the size of the segments, can mean multiple large vehicle journeys and special load vehicles. This can cause issues with prints in remote or difficult to access areas and largely discounts this method for extra-terrestrial applications. As the segments are large and heavy, overhead cranage is also required.

By breaking the structure into several parts as opposed to one continuous extrusion the structural integrity of buildings created in this manner would also be compromised and could restrict the number of floors that can be accommodated using this method.

Robotic Printers

Fig 6: Cazza X1

Robotic Printers are mobile units capable of extruding a cement substrate or laying brick and other construction materials. Robotic printers are not fixed to a specific location and move about on wheels or tracks giving them a high manoeuvrability.

Pros and Cons:
Construction 3D printers of this variety typically have an edge over other C3DP methods in terms of scalability since they have no fixed reference point and can theoretically build anywhere accessible to humans.

This type of C3DP technology is still in early development and current technology is slow and awkward. This will improve as robotics in general improve, however the speed at which this type of printer can operate is tempered by the fact that more delta movement is required to complete a given print, especially so for Robotic printers that do not extrude material but instead place prefabricated parts. This type is also restricted by the height at which it can print and will require overhead cranage to move into place when building above ground floor.

Another disadvantage of this printer type is accuracy of print. As there is no fixed reference point for the print, these types of printers rely on cameras and sensory data to determine where to print next which can lead to quality issues and miscalculations.

1.1.2 Benefits Matrix

To compare the benefits of each printer type, a benefits matrix has been used to assess various factors that are important to C3DP technology. These include scalability, print speed and quality and setup complexity. Each factor has been given a score from 1 to 5, 5 being absolute best and 1 being worst.

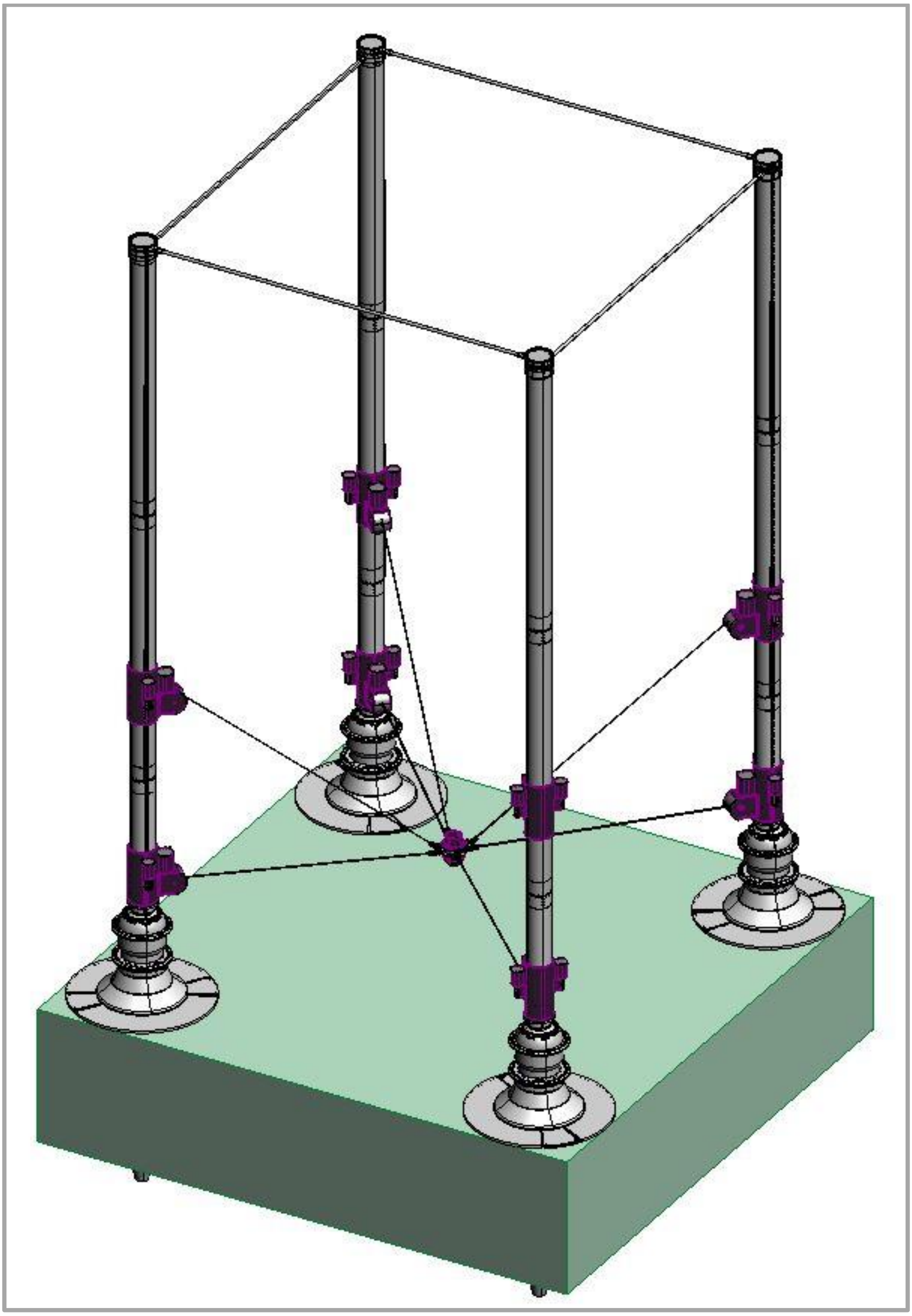
Factor	Rotary Arm	Overhead Crane	Modular	Robotic
Package Weight	4	2	1	4
Print Speed	4	4	3	1
Scalability	2	2	4	2
Print Quality	3	4	4	2
Efficiency	4	3	2	2
Set-up Time	4	1	5	4
logistics	3	1	1	2
Total	**24**	**17**	**20**	**17**

In this assessment we can see that Rotary Arm C3D Printers are the most favourable of the printer types reviewed. This is largely because this type can be set up and utilised in most scenarios thanks to its small package weight/size and minimal set-up time. Rotary Arm printers are predominantly limited by the scalability factor of the technology. Overhead Crane printers scored poorly due to long setup time and the logistical issues related to delivering such large cumbersome structures but scored the best for print quality and speed.

Modular printing was the most proficient in set-up thanks to the fact that segments are built ahead of assembly. This means setup time is minimal or non-existent for this type of printer. As the modular printers use traditional overhead crane 3D printing to generate the structure segments, the print quality is comparably good, however delivering the manufactured segments to location requires a comparatively large package weight and is logistically challenging.

Robotic Arms require very little setup and are typically lighter than most other C3DP methods, but print speed, quality and efficiency all suffer from increase in delta movement of the Extruder/Arm to complete a given print and the infancy of current robotic technology. Scalability is also relatively restricted with robotic printers.

2.0.0 Suspended Additive Layer Extrusion Machine Proposal



Demonstrative representation of the SALEM Printer. Print envelope shown is approx. $4m^3$

2.1.0 Introduction

This product concept is a Construction Additive Layer Printer that would be capable of printing building structures of virtually any size for a fraction of the time and cost of comparable brick laying methods.

The printer features an Extruder for printing the cement, 8 Hoists for suspending and controlling the location of the Extruder; and a 4-legged support structure to provide the variable Hoists with a fixed axis. The Extruder is connected to all 8 Hoists via cables and cement is fed to the Extruder via a Tank and Pump system located on the ground. The printer would be capable of printing any aggregate/cement mixture that can be pumped, enabling structures to be built on Mars without construction materials brought from Earth.

The printer works by triangulating the position of the extruder based on the extension length of the Hoist cables and the relative positions of each Hoist. The Hoists are able to traverse the length of the Support Structure and will rise gradually as more layers are added to the printed cement structure. The variable Hoists can extend or retract the cables and by extending some cables and retracting others, it is possible to move the relative position of the Extruder in a fully controlled manner. This allows the Printer to print any shape within a 3-dimensional print envelope. The Printer could be capable of printing with millimetre accuracy once fully developed and will be capable of printing far more complex structures than current construction methods feasibly allow. Facilities can be integrated into the printed structures to utilise the elements. For instance, channels can be designed into buildings to collect rainwater or to control air flow around the building and distribute heat evenly. The Extruder should be capable of mapping the ground which would allow it to print an initial foundation over any ground regardless of shape.

The Printer Structure is composed of four legs and a variable number of Support Beams and as each leg is independent of the others, it is permissible to secure them at any practical length apart, from as little as 2 meters separation, to upwards of 100 meters. The legs are built up of many individual Grid Pieces which enables the height of the printing envelope to vary to suit the construction project requirements. When erecting the printer there are several calibration operations which set the starting positions of the variable Hoists, Support Legs and Extruder as well as identifies ground height and slope of the print envelope. This means that it is unnecessary to position the legs perfectly square as the print envelope is entirely relative.

Due to the modular design of the printer it can be disassembled and compacted small enough to be transported by a single mini-van for smaller applications. As the Hoists are motorised and capable of travelling along the Legs it is technically feasible to assemble the Printer using no overhead crane and, with the right tooling, can be assembled by just 2 people. This makes it an ideal concept for erecting permanent structures in hard to reach or uninhabited locations such as Mars.

The travel speed of the Extruder is fixed only by the speed of the cable spool and the drying time of the cement meaning that extremely rapid printing speeds can be achieved. If we assume that it is at least possible to print at the same travel speed of the average human walking (about 1.6mph) it will be possible to extrude a 1000 sq. ft. structure in less than 24 hours. Another feature that decreases print time is a variable diameter Extrusion Nozzle enabling the Printer to outline the print using a thin cement layer, then fill the profile in using a thick cement layer, drastically reducing the total amount of Extruder movement required to complete a single layer whilst also improving the quality of structure definition.

2.1.1 Product Requirements

Calibration & Assembly

As the SALEM Printer does not have a fixed print envelope, it must be possible to calibrate all attributes of the printer on site, during assembly. This should be as simple as possible and automatic where applicable and final calibration, that is calibration of the full assembly, should take no longer than 24 hours to complete. Once set-up the printer should require no additional calibration for operation except in exceptional circumstances such as natural weather phenomena events. The intention is to be able to assemble the SALEM printer without any overhead craneage and with a crew of just two people. To achieve this most individual components must be made light enough to be manually lifted by two people.

Maintenance

The SALEM Printer is designed for applications that could require up to a year of continuous operation (Vertical Farms) and therefore must be resilient and easy to maintain. The printer should require no more than 100 hours of scheduled maintenance per year and must allow for rapid in situ replacement of parts to prevent the need for major disassembly should a problem occur during print. This extends to electronic components which must feature standardised connections to allow for easy repair in remote locations without the need to bring full spare harnesses. Structural parts and housings must be operable for at least 10,000 hours without scheduled maintenance so should be resistant to all types of corrosion and wear for at least 8 years. All parts for the Hoists and Extruder must be replaceable on site and fasteners must also be standardised across the printer.

Functionality

As the printer will be used for structural prints that could take up to a year to complete it must be able to maintain long periods of continuous operation. At a minimum, the printer must be able to continually operate for 360 hours (15 days) without interruption. Ideally the printer should be able to operate continually much longer. To allow for the manufacture of Vertical Farms, the printer must be able to print to a height of at least 100 meters and be capable of printing to millimetre accuracy. The basic function of the printer operation relies on being able to calculate required cable extension lengths for any given reference point within a relative print envelope, so in order to determine enough information to achieve this the printer must be able to measure the distance between all Hoists and the Extruder. If an incident occurs that requires the print to be paused and maintenance to be completed, the printer must be capable of retracting the Extruder to a safe location then find its last position and resume print when repairs are completed. Lastly, the printer should recognise a fault automatically to reduce downtime.

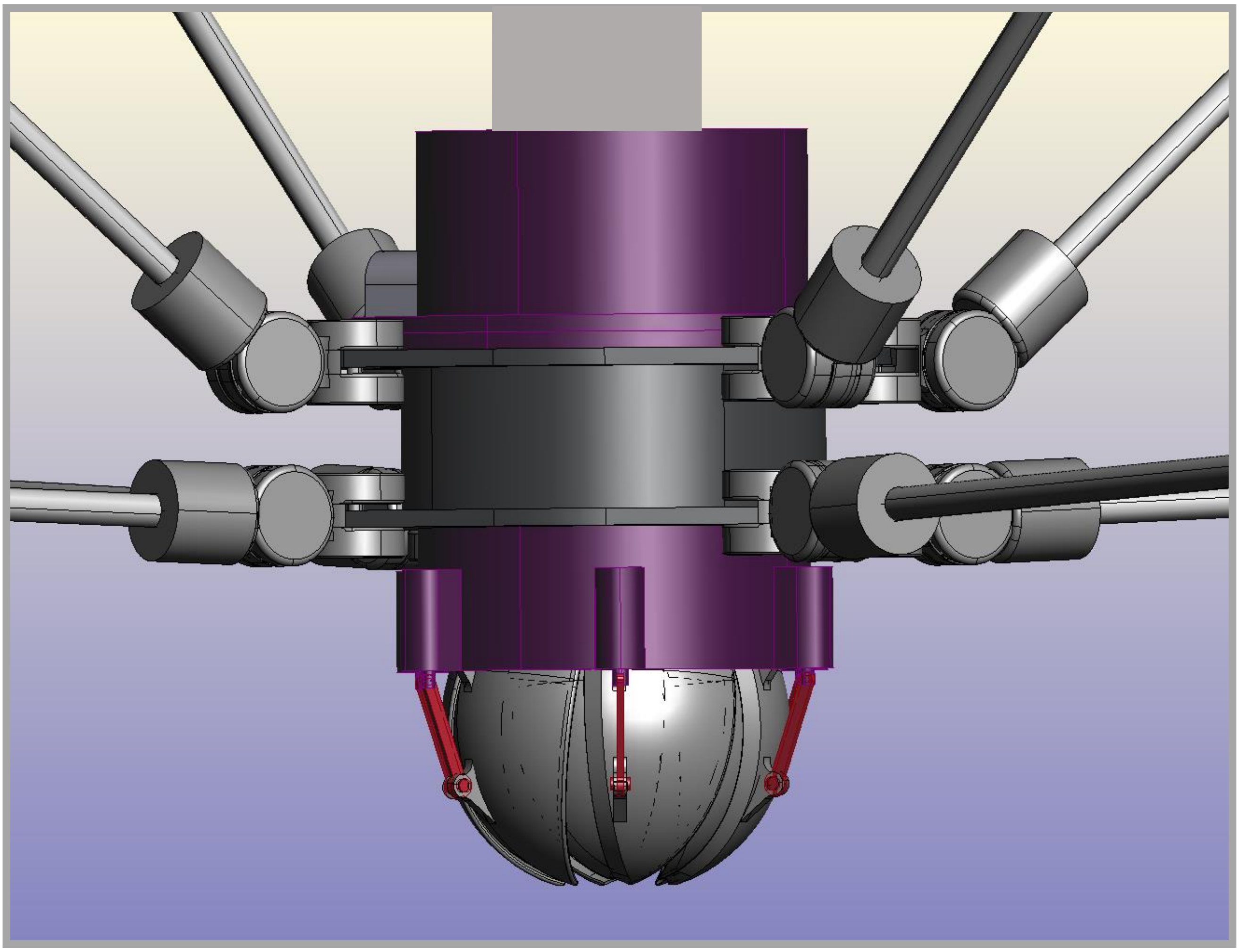
Design Practicality

To ensure the Printer can be improved upon without being entirely replaced, it must be designed in a modular fashion with new parts being backwards compatible where possible. There are also a set of other practical requirements that mainly apply to application on Mars. In order to transport the printer to Mars it must be light enough and compact enough to fit inside the hull of a single Big Falcon Rocket with tooling and enough cement to complete all print tests to certify the SALEM Printer. As a result of this, tooling should constitute no more than 20% of the total Printer weight. In order to be able to print on Mars self-sufficiently all aggregates and raw materials required for printing must be procurable on Mars. The printer must also be able to maintain a stable core temperature in extremely cold environments.

SALEM Printer Requirements Summary

Requirement	Type	Application
Must be able to completely calibrate on site	Calibration & Assy	All
Must be simple to calibrate	Calibration & Assy	All
Must be able to complete final calibration in less than 24 hours	Calibration & Assy	All
Should not require secondary calibration after initial set up under normal circumstances	Calibration & Assy	All
Must be able to calibrate dimensions independently	Calibration & Assy	All
Printer design should accommodate assembly	Calibration & Assy	All
80% of parts must be less than 44 kg to allow for a 2-person manual lift	Calibration & Assy	All
Should require less than 100 hours maintenance a year	Maintenance	All
Must allow rapid (less than 4 hours down time) in situ replacement of parts	Maintenance	All
All electronics must use standardised connections	Maintenance	All
Electronics must be modular and easy to replace	Maintenance	All
Variable Jig housing, extruder housing and Structural parts should be operable for at least 10,000 hours before requiring maintenance	Maintenance	All
All parts for the extruder and variable jigs must be replaceable on site	Maintenance	All
Must resist corrosion in all weathers for at least 8 years	Maintenance	All
Nuts, bolts and other fasteners must be standardised, and variance minimised as much as is practical	Maintenance	All
Must be continually operable for at least 360 hours	Functionality	All
Should be continually operable for at least 1,500 hours	Functionality	All
Must be able to print to a height of at least 100 meters	Functionality	All
Must be able to sense cable length change to a tolerance of +/- 2mm	Functionality	All
Must be able to calculate correct cable length based on relative positions	Functionality	All
Must be able to sense relative positions of all Variable Jigs and Extruder	Functionality	All
Must be able to stop print and retract extruder and find the last position automatically	Functionality	All
Should be able to diagnose 90% of faults automatically	Functionality	All
Must be modular to allow for design iterations to individual elements	Practicality	All
New parts should be backwards compatible	Practicality	All
Tooling should constitute no more than 20% of the total weight of the printer itself.	Practicality	Mars
Must be compact-able enough to fit in the hull of a Big Falcon Rocket	Practicality	Mars
Must be light enough to be launched to Mars on a Big Falcon Rocket with tooling at least 10 tons of cement.	Practicality	Mars
Must be capable of printing using aggregates and other materials found on Mars	Practicality	Mars
Must be capable of maintaining a temperature of 20 Degrees C in the Cement Delivery System and Extruder	Practicality	Mars

2.2.0 Extruder



Representation of the Extruder suspended in the Cradle

The Extruder is the SALEM Printer module responsible for extruding the cement print profile. It is held in position and manipulated by the 8 Hoists which all attach to the Extruder Cradle. Cement is fed to the Extruder via a hose attached to the top of the Extruder Housing and pump inside the Housing controls flow from the cement feed to the Nozzle Chamber. The Nozzle Chamber is a variable profile extrusion nozzle and is the exit point for the cement. By extending or retracting actuators located at the bottom of the Extruder housing, the nozzle open and closes altering the size and shape of the print profile.

2.2.1 Requirements

Flow

To generate a suitable print the Extruder must, at the very least, be able to provide a consistent and measurable flow of material. Print times could be drastically reduced with the capability to vary filament diameter by creating an initial, accurate thin outline then filling it in with a larger diameter flow. The Extruder should be able to cease cement flow fast enough to prevent run off when moving to a new location or in response to an emergency. This will also allow the print to be paused at any time. The print speed should be at least comparable or better to current C3DP technologies so to stay competitive should be capable of printing a 1000 sq. ft. building in 24 hours or less.

Operability

The printer intention is to be applicative to any cement construction project and in conditions, in some cases, entirely alien to those experienced-on earth. Mars ground temperature for instance can drop to less than -240 degrees F (120K, -153 degrees C) so the Extruder must be able to continue to operate in extreme conditions considering not only temperature but pressure, humidity, wind speed, static discharge and seismology to name a few examples. To save on package delivery for isolated and hard to reach locations the printer must be able to print sand and aggregate found on site.

Weight

As the basic concept of this C3DP requires suspension of the Extruder, weight is a pivotal factor that should be mitigated as much as possible. A heavy Extruder will print far poorer than a light Extruder. If the Extruder is too heavy the Hoist Motors will struggle to control the inertia of the mass meaning that for the same quality print, the heavier Extruder will require bulkier Hoist Motors and Cables and will expend more energy in operation. If too much torque is required to maintain and manipulate the Extruder suspended location, then the printer could be at risk of collapsing. To avoid this the largest part of the material extrusion process must be independent of the Extruder and preferably be ground based. Cement stores, Pumping system and electrical components must be managed on the ground where possible.

Maintenance and Assembly

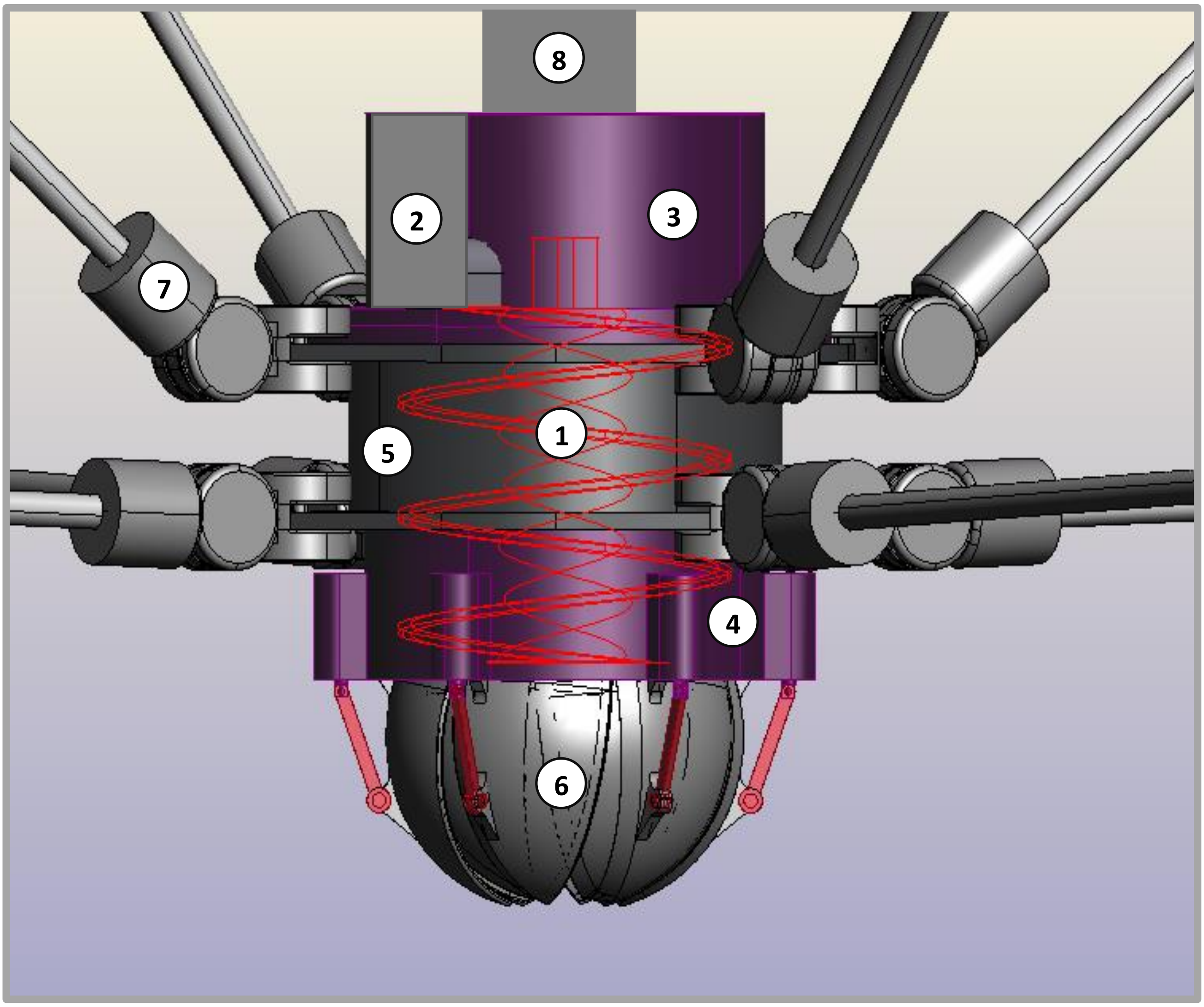
To reduce downtime for maintenance and fault recovery as well as simplifying assembly the Extruder must be removable without disassembling or slackening the cables. The Extruder, in effect, should be "plug and play" requiring minimal effort to disconnect and swap out mid-print.

Extruder Requirements Summary

Requirement	Type	Application
Filament flow must be maintainable within +/-1% of intended speed	Flow	All
Must be able to print variable width ranging from <1cm to >5cm	Flow	All
Must be able to stop cement extrusion in <1s	Flow	All
Must be able to print at, at least 1.6m/s	Flow	All
Must be operable between -40 and 120 degrees F	Operability	All
Must be operable at a temperature of -200 degrees F	Operability	Mars Printer
Must be electrically grounded when in operation	Operability	All
Should have a secondary sense of relative location	Operability	All
Should be able to detect 99% of malfunction automatically	Operability	All
Should be able to print any type of ground aggregate	Operability	All
Must weigh no more than 44 kg	Weight	All
Should be able to disassemble from printer set-up in less than 1 hour.	Maintenance	All
Must be able to remove Extruder without disconnecting/ slackening Cables	Maintenance	All

2.2.2 Extruder Concept Design

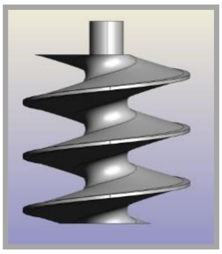
To achieve the weight requirements, the Extruder concept has been kept simple and consists of very few elements. Primary pumping has been assumed as part of the Cement Processing based on the ground and a secondary Screw Pump has been designed into the Extruder head to control the flow before exiting the Nozzle. The Nozzle consists of 6 concentric plates that can expand or retract depending on the extension of Control Rods manipulated by actuators located on the Extruder Housing. The Cables are suspended on a Cradle ring that can be detached from the Extruder.



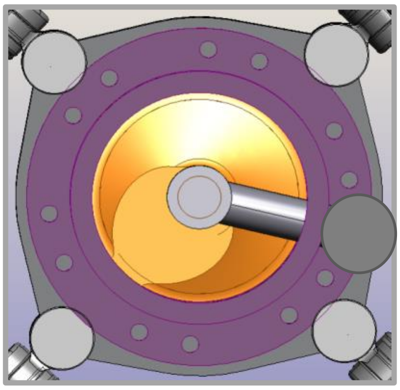
Annotated representation of the Extruder suspended in the Cradle

No	Component Name
1	Pump Screw
2	Pump Screw Drive System
3	Upper Extruder Housing
4	Lower Extruder Housing
5	Extruder Cradle
6	Cement Nozzle
7	Cables
8	Cement Hose

1. Pump Screw


Pump Screw

The Pump Screw is a worm screw seated vertically inside the Extruder housing that is used to control cement flow. As the Pump Screw turns it draws cement down to the Cement Nozzle and by alternating the RPM of the Screw the cement flow can be increased or stemmed.

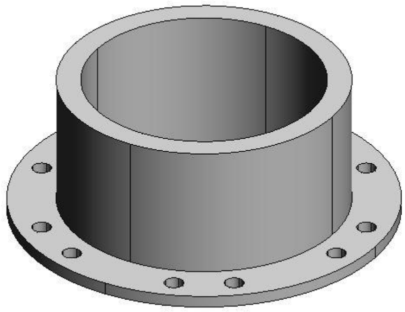

Top down view of Extruder

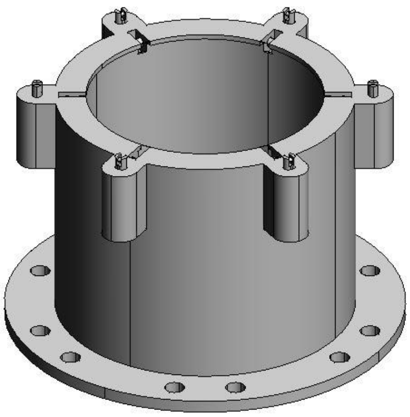
2. Pump Screw Drive System

This is the drive system that turns the Screw Pump. The Screw and Drive System are responsible for controlling the flow of cement. Primary pumping will be completed on ground and the Screw Pump functions as a control valve by changing revolution speed of the Screw. The flow rate can be calculated and directed to enable optimal Print Speed by measuring RPM of the Screw and translating it into Laminar Flow.

3. Upper Extruder Housing

The Upper Extruder Housing is the topmost part of the Extruder housing. The Extruder Housing is split into 2 parts to enable the Pump Screw to be replaced/ removed for maintenance in a simple and easy manner. In more mature design iterations the Extruder Housing will feature a click on/click off style connection for the Cement hose and a motor system for driving the Pump Screw.


Upper Extruder Housing

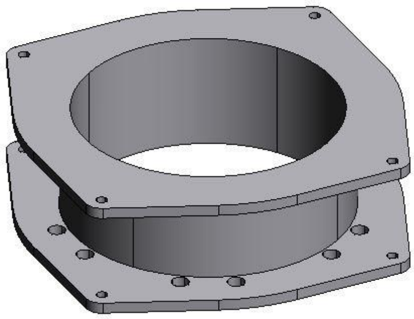

Lower Extruder Housing

4. Lower Extruder Housing

The Lower Extruder Housing is the bottom half of the Extruder Housing. This is the section of housing that interfaces with the Cement Nozzle. The Nozzle Actuators are fixed to the housing and the Nozzle Plates pivot on the internal face. In later iterations the Lower Extruder Housing will feature sensors that can detect and map the surface. This will enable the Extruder to scan the surface and then print an even foundation for the structure to be built on. The sensors will also provide a secondary feedback loop to the Variable Hoists so fine tuning of the Extruder movement can be achieved and correct height is constantly maintained.

5. Extruder Cradle

The Extruder Cradle is the ring that the cables are anchored to. This ring is conceptualised as a separate component to the Lower Extruder Housing so that the Extruder assembly can be detached from the Printer without losing calibration by slackening the cables, thus reducing the downtime should a malfunction with the Extruder occur.

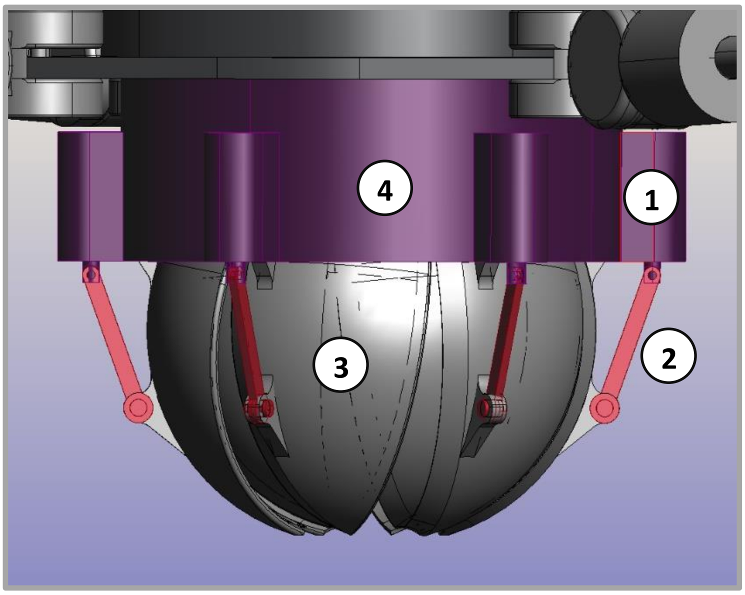

Extruder Cradle

6. Cement Hose

The Cement Hose feeds cement from the ground-based Cement Processing unit to the Extruder. The Hose will be made of a flexible material to enable the Extruder to move freely when in print. A shut off valve is required at the Extruder end so that it is possible to disconnect the Extruder without any significant cement run off.

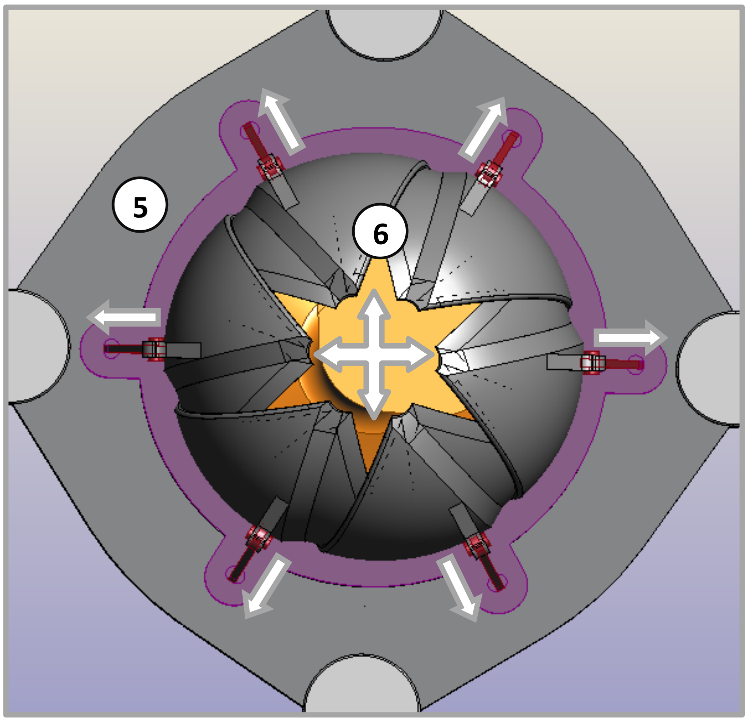
8. Cement Nozzle Sub-Assembly

The Cement Nozzle controls the size of the extruded material by opening and closing the 6 Nozzle Plates which are controlled by Actuators and Control Rods fixed to the Lower Extruder Housing. The concept design is for demonstration purposes only, later iterations should be capable of opening in a circular profile by angling the Nozzle Actuators and reshaping the Nozzle Plates.



Annotated side profile of Extruder Nozzle Assembly

No	Component Name
1	Actuator
2	Control Rod
3	Nozzle Plate
4	Lower Extruder Housing
5	Extruder Cradle
6	Nozzle Assembly



Annotated bottom up view of the suspended Extruder

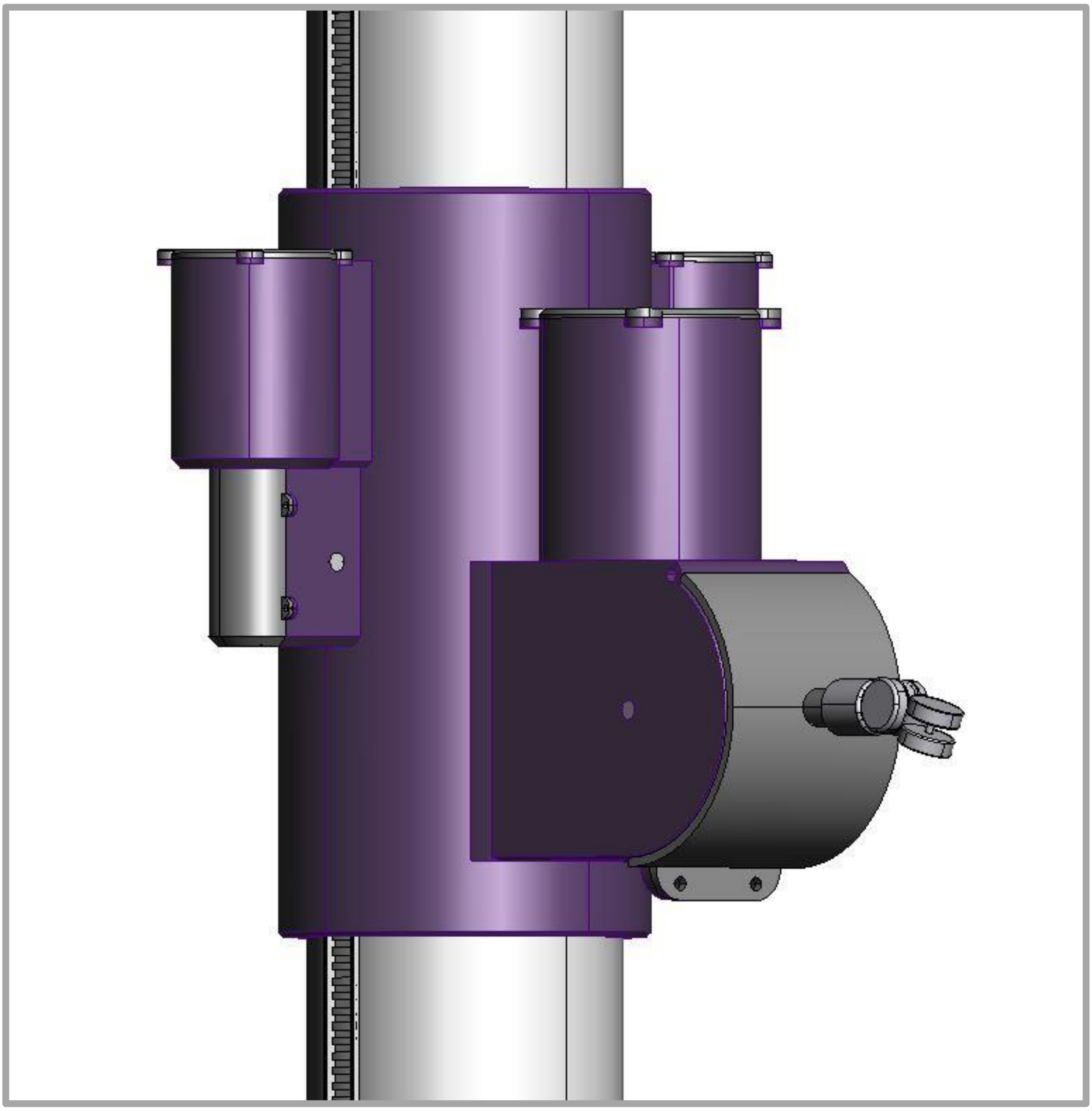
2.2.3 Weight

The initial concept design for the Extruder is a little heavy, weighing in at 56.2Kg. This means that, as is, the design does not meet requirements and cannot be final assembled manually safely as a complete module. This total does however, include the weight of the Cable Hoist Ring and for the 2-person assembly sequence this component is assembled prior to marrying the Extruder to the Printer assembly. If we remove this component from the total for the Extruder, the weight is reduced to just below 47kg, which is only just outside of requirements. For a 2-person manual lift of the Extruder, we would only need to reduce the overall Extruder weight by a few kilos, which could be achieved by thinning the housing walls or reducing the scale of the Extruder. It may even be feasible to design the Screw Pump in Aluminium instead of Titanium which would save 2-3Kg, however this may have a detrimental effect on the cycle life of this component.

Extruder Concept Weight Assessment				
Part Name	**QTY**	**Material**	**Estimate Type**	**Mass (Kg)**
Screw Pump	1	Titanium	Initial CAD	11.88
Screw Pump Drive Housing	1	Aluminium	Initial CAD	0.90
Screw Pump Drive Chain	1	Steel	Allowance	0.50
Screw Pump Motor	1	Mix (Heavy)	Allowance	4.00
Upper Extruder Housing	1	Aluminium	Initial CAD	6.70
Lower Extruder Housing (incl Nozzle Actuators)	1	Aluminium	Initial CAD	11.44
Extruder Cradle	1	Titanium	Initial CAD	9.68
Nozzle Plate	6	Titanium	Initial CAD	2.70
Nozzle Connection Rod	6	Titanium	Initial CAD	0.12
12M 40 Bolt & Nut	12	C. Steel	Calculation	0.52
Cement Hose attachment	1	Titanium	Allowance	6.00
Electrical Details	1	Mix (Light)	Allowance	2.00
Total Extruder Assembly Weight (Dry)				**56.2 Kg**
Extruder Assembly Weight (No Extruder Cradle)				**46.6 Kg**

For snapshots of the CAD model material properties, see **Appendix 2 – Material Mass Properties**

2.3.0 Hoists



Representation of the Hoist mounted to the Support Structure

The Hoists control and manipulate the location of the Extruder within the print envelope by altering the extension length of a cable attached to the Extruder. There are 8 Hoists in a typical SALEM Printer setup. 2 Hoists are located on each Structure Support leg, the top Hoists carry the majority of the Extruder weight and maintain the height of the Extruder in relation to the ground. The bottom four Hoists manipulate the 2-dimensional profile of the print. Hoists can automatically traverse along the Structure Support leg length by interfacing with a track built into the leg design.

2.3.1 Requirements

Operability

The Variable Hoist must be able to determine its relative position and the position of every other Hoist and Extruder based on sensory and calculated data. This is to ensure cables are extended/ retracted correctly to control the Extruder print path. Another key operability requirement is the speed of the cable extension and retraction. The Printer must be capable of printing at sufficient speed to print an entire house with 24 hours of use. If the Hoist Cables can extend/retract as fast as walking speed (1.6m/s) this will be possible.

Weight

Each individual Hoist must weigh no more than the manual handling limit for a two man lift to allow for assembly of the printer without an overhead crane. The weight of the Hoists will determine to a large degree, what the maximum print height of the printer can be due to deflection of the Support Structure.

Maintenance and Assembly

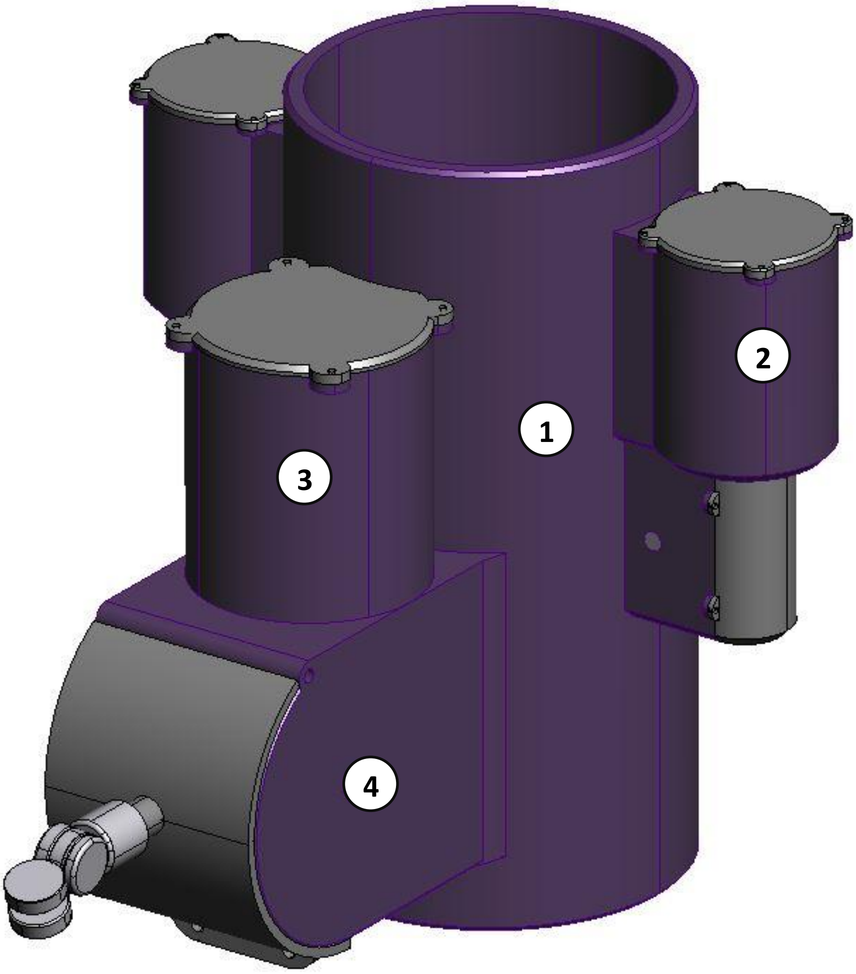
The Hoists must be easily calibrated on printer set up and in order to achieve a 2-person, no crane assembly, the Track Motors must be capable of lifting the weight of the Hoist plus 1 2m grid piece, 1 average human and approx. 20kg of additional tooling.

Hoist Requirements Summary

Requirement	Type	Application
Cable Motors Must be capable of lifting 100Kg each	Operability	All
Track Motors must be capable of lifting 120Kg Each	Operability	All
Must have a secondary sense of cable extrusion length.	Operability	All
Max cable Travel Speed must be at least 1.6m/s	Operability	All
Must be operable between -40 and 120 degrees F	Operability	All
Must be operable at a temperature of -200 degrees F	Operability	Mars Printer
Must be grounded when in operation	Operability	All
Should have a secondary sense of relative location of all other Hoists and Extruder.	Operability	All
Should be able to detect 99% of malfunction automatically	Maintenance	All
Should have emergency braking features to prevent damage from malfunction.	Operability	All
Must weigh no more than 44Kg as an assembly	Weight	All
Must be able to disassemble from printer set-up in less than 2 hours.	Maintenance	All
Must be able to restart print from pause after a hoist has been removed from the assembly	Maintenance	All

2.3.2 Variable Hoist Concept Design

The Hoist concept design consists of a tubular housing that slides over the Leg Structure Track, 3 Motors & Gears and a Cable & Spool. Two of the Motors are used to lift the Hoist vertically along the Leg Structure Track and the final Motor is used to control the Cable and Spool. The Hoist will determine extension length of the Cable through two means; firstly, through calculation based on RPM and gear ratios, alternately it will determine extension length through measurements collected by various sensors.



Annotated isometric view of the Hoist concept

No	Component Name
1	Housing
2	Track Motor Sub-Assembly
3	Spool Motor
4	Spool Sub Assembly

2.3.2 Hoist Spool Sub-Assembly

The Hoist Spool Sub-Assembly comprises of; a Spool and Cable, a Servo Motor and an assortment of Gears. The Motor is stepped down through the Gear arrangement to turn the Spool and by measuring the RPM of the Servomotor, it is possible to calculate and control the travel speed of the Cable.

The initial design has an arrangement of four gears. Connected to the Spool Motor is a 26-tooth gear, which turns a 16-tooth gear on a lower shaft. The shaft has a worm screw driving a 57-tooth gear connected to the cable spool. When the Spool Motor is in operation the Spool will turn at a step-down rate of the speed of the Motor. To find the step-down ratio we can break the gear arrangement into two parts. The first is the Spool Motor Gear (T26) and the lower Shaft Gear (T16).

$$Step\ Down\ Rate = \frac{Drive\ Gear(G_1)}{Driven\ Gear(G_2)}$$

Where G_1 is 26 and G_2 is 16 we get:

$$Step\ Down\ Rate = \frac{26}{16} = 1.625$$

This means for every revolution of the spool motor shaft; the lower shaft will turn 1.625 times. The lower shaft turns a worm screw and every revolution this screw makes, turns a 57-tooth gear one tooth. For the whole system the step-down ratio would therefore be:

$$Step\ Down = \frac{57}{1.625} = 35.08$$

The current arrangement of Gears provides a step down of approx. 1:35. Assuming the Servomotor would be capable of operating at 18,000RPM (300RPS), the RPM of the Cable Spool can be found by dividing speed by the step-down ratio:

$$Cable\ Spool\ Speed = \frac{300}{35} = 8.57RPS$$

If we consider that the Cable Spool will have a minimum diameter of 2cm we can find the Max Travel Speed of the cable:

$$Max\ Cable\ Speed = Spool\ Circumference\ \times Spool\ RPS$$
$$Max\ Cable\ Speed = (2\pi \times 0.01) \times 8.57 = 0.54m/s$$

We need to achieve a speed of 1.6m/s to meet requirements so our current step-down arrangement will need to change or a higher Motor RPM needs achieving. As 18,000RPM is already exceedingly high, the best route would be to alter the gear arrangement and up the Motor power rate. We can find the required step-down ratio for our gear arrangement with the following equation:

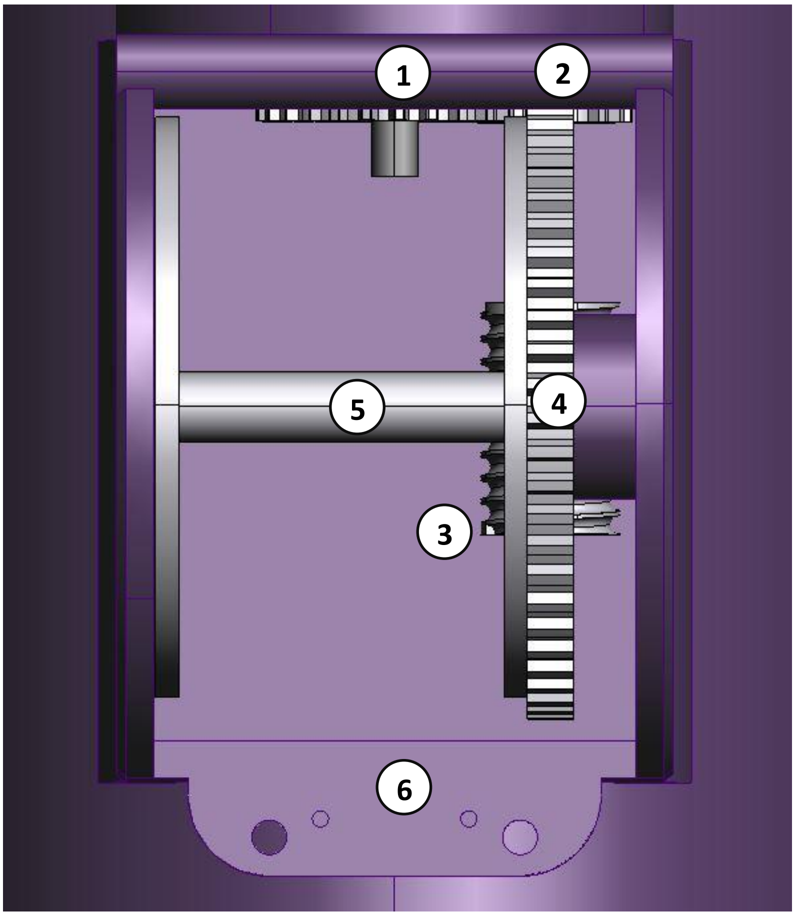
$$Gear\ Ratio = \frac{Max\ RPS \times Spool\ Circumferance}{Travel\ Speed}$$
$$Gear\ Ratio = \frac{300 \times (2\pi \times 0.01)}{1.6} = 11.78$$

The step-down ratio for our Spool can be no more than 1:12 if we are to achieve a travel speed of 1.6m/s at a motor speed of 18,000RPM (300RPS).

If we increase the teeth on the 26-tooth gear to 32, decrease the 16-tooth gear to 8 teeth and reduce the 57-tooth gear to 40 teeth we achieve a step-down ratio of 1:10 thereby increasing the Max Print Speed to just shy of 1.9m/s allowing the system to realistically achieve travel speed requirements. Reducing the stepdown ratio will, however, influence the lifting capabilities of the Hoist which, all things considered, is of greater importance than the print speed. The final design will need to consider both speed and lift carefully and deliver a reasonable compromise.

The Hoist Motors must be capable of lifting and manipulating the Extruder and Cement Hose Assembly. In ***Appendix 1 - Printer Energy Consumption & Production*** we calculate that the Hoist Motors would require a Power Rate of at least 1.85Kw to operate at current specification, to achieve higher printer speeds this power rate will increase, limiting its usage where energy is a premium.

No	Component Name
1	26 Tooth Gear
2	16 Tooth Gear
3	Worm Screw
4	57 Tooth Gear
5	Spool
6	Housing



Annotated internal view of the Hoist Spool Gear Arrangement

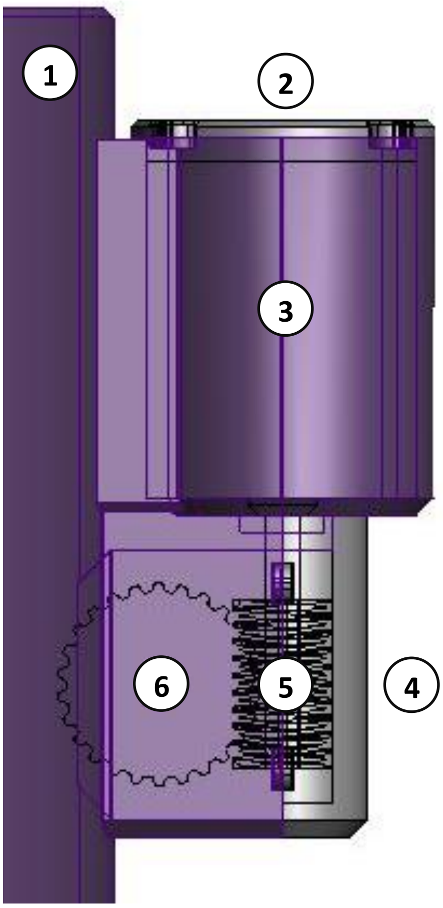
Later iterations of the Hoist Spool Assembly design will feature a sensor(s) at the cable exit point that measures the cable extension length and compares it to the calculated extension length (calculated from Motor RPM). If the two measurements mismatch the printer will pause to protect the extruded structure quality and an error code will be flagged. Other sensors will be strategically placed around the Hoist housing that will be used to identify the relative positions of the other Hoists and Extruder.

2.3.2 Hoist Track Sub-Assembly

The Hoist is able to traverse the length of the Support Leg by utilising two motors and gears that are situated parallel along the Hoist housing. The Track motors turn worm screws that drive corresponding gears and the teeth of the gears interlock with tracks on the Grid Pieces. The current concept design Track Tooth length is 8mm. This means that if the Motors are capable of 6000 RPM, the Hoist will raise/lower at a Max speed of 0.08m/s. To increase the speed of this function the length of the track teeth could be increased, or the number of teeth of the Track Gear can be reduced. In any case, given that the Hoist will only need to raise once per layer by approx. 0.025m it is not particularly detrimental to the overall print speed that this element is relatively slow, and the current design should suffice.

One consideration that needs to be made is how this travel speed will affect the time it takes to assemble the printer using the 2-person assembly method as this requires a reasonably large amount of movement of the Hoists up and down the Support Legs to assemble the Grid Pieces. For smaller (single storey) Construction Projects this should have minimal impact to assembly time, but for larger (Multi-Storey) Projects the Track travel speed may prove cumbersome.

In **Appendix 1 - Printer Energy Consumption & Production**, we calculate that the Hoist Track Motors would each need a power rate of at least 0.132Kwh to function at the rate discussed here.



Annotated internal view of the Hoist Track Gear Arrangement

No	Component Name
1	Hoist Housing
2	Track Motor Cover
3	Track Motor
4	Track Gear Cover
5	Worm Screw
6	Track Gear

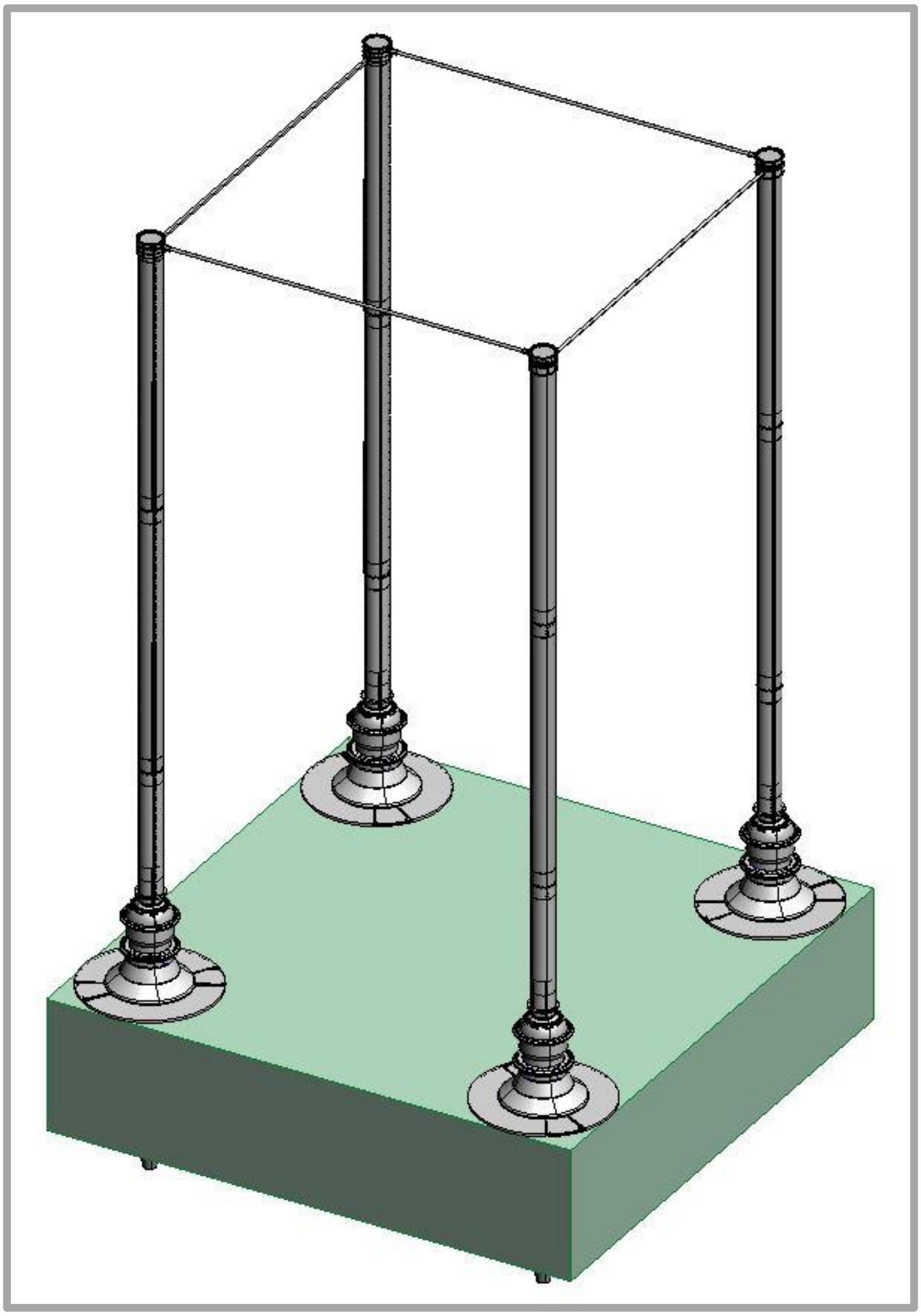
2.3.3 Weight

The concept design for the Hoist is currently within weight requirements at just below 39Kg however it should be considered that to assemble the Hoists using the 2-person assembly method there is a requirement to lift above shoulder height. It would still be beneficial from a safety point of view to reduce the weight further and the key opportunity to reduce weight is by thinning the walls of the Hoist Housing, which are currently 10mm thick. This is likely to be far thicker than structurally required.

Hoist Concept Weight Assessment				
Part Name	**QTY**	**Material**	**Estimate Type**	**Mass (Kg)**
Hoist Housing	1	Aluminium	Initial CAD	11.54
Cable Spool	1	Titanium	Initial CAD	5.80
Cable (5m)	1	C. Steel	Initial CAD	0.77
Spool Cover	1	Aluminium	Initial CAD	0.38
16 Tooth Gear	1	Titanium	Initial CAD	0.33
26 Tooth Gear	3	Titanium	Initial CAD	1.92
57 Tooth Gear	1	Titanium	Initial CAD	0.62
Worm Screw	3	Titanium	Initial CAD	0.12
Hoist Motor (2Kw 18,000 RPM)	1	Mix (Heavy)	Initial CAD	4.73
Track Motor (0.2Kw 6,000 RPM)	2	Mix (Heavy)	Initial CAD	5.10
Hoist Link	1	Titanium	Initial CAD	1.43
Extruder Link	1	Titanium	Initial CAD	0.91
Bearings	9	Mix (Heavy)	Calculation	1.12
Spool Shaft	2	Titanium	Initial CAD	0.13
Track Gear Shaft	2	Titanium	Allowance	0.06
Hoist Motor Cover	1	Aluminium	Initial CAD	1.53
M6 25 Bolt & Nut	22	C. Steel	Calculation	0.20
Sensors	10	Mix (Light)	Allowance	0.30
Electrical Details	1	Mix (Light)	Allowance	2.00
Total Hoist Assembly Weight				**38.9 Kg**

For snapshots of the CAD model material properties, see **Appendix 2 – Material Mass Properties**

2.4.0 Support Structure



Representation of the SALEM Support Structure Assembly

2.4.1 Requirements

Integrity

The Support Structure provides the printer with the only fixed axis and as such, it is imperative that it remains entirely fixed in position. Deflection should be minimised as much as is practically possible and it should be possible to easily and reliably calibrate each leg to true vertical, as tiny deflections in this axis will potentially cause large, noticeable misalignments at greater operation elevations. The Printer Structure must not lose calibration once final printer assembly is complete and if, for any reason this does happen, the printer must pause the print and flag the misalignment until it has been corrected.

Assembly

As the printer is intended to be used in all terrains without first laying a foundation, it is important that the printer structure can be erected and calibrated on uneven surfaces at mixed elevations and on angled grounding. As with all other elements of the SALEM printer, no individual component should weigh more than the maximum safe manual handling limit for a 2-person lift. This is to ensure that a 2-person assembly is possible without additional cranage.

Maintenance

The Structure should require little to no maintenance from print to print and any maintenance activities should be decoupled from the overall printer. This is to say, if maintenance is required on part of the Support Structure, it should be possible to do so without decommissioning the entire printer for the duration of the maintenance. To achieve this, components must be standardised and modular to allow for swapping between sets.

Durability

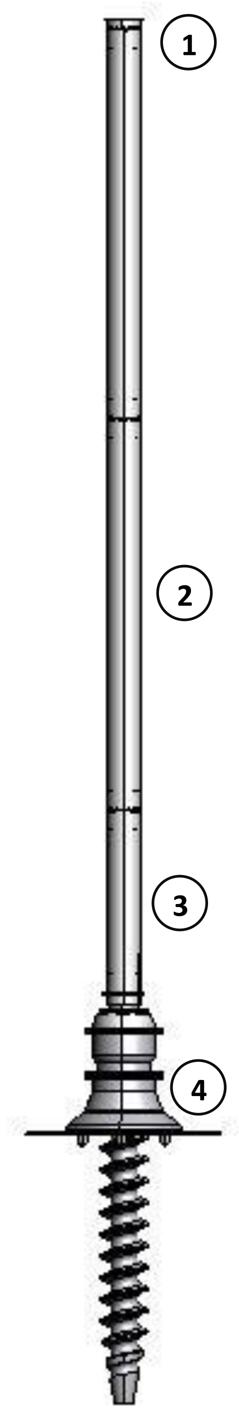
The Support Structure must be able to continue to operate in extreme conditions considering not only temperature but humidity, wind speed, static discharge and seismic activity to name a few examples. The Structure must be durable enough to outlast the Extruder and Hoists and resist corrosion for an indefinite amount of time.

Support Structure Requirements Summary

Requirement	Type	Application
Must be easily erected on site on uneven surfaces	Assembly	All
Must be able to erect in less than one week	Assembly	All
Must be able to fix structure feet at variable heights	Assembly	All
Must be able to fix structure feet at an angle of at least 15 Degrees	Assembly	All
Should be erect-able without an overhead crane	Assembly	All
Must not require structure feet to be aligned at perfect 90-degree angles	Assembly	All
Must be erect-able with a 2-person crew	Assembly	All
No Individual component should weigh more than 44kg	Assembly	All
Structure feet should align automatically	Assembly	All
Should require no regular maintenance	Maintenance	All
Components Must be standardised for easy replacement	Maintenance	All
Should be able to detect 90% of malfunction automatically	Integrity	All
Must maintain calibration during print	Integrity	All
Must not Deflect more than 1 Degree when in operation	Integrity	All
Must be operable between -200 and 120 degrees F	Durability	All
Should resist all Extreme weather scenarios	Durability	All

2.4.2 Support Structure Concept Design

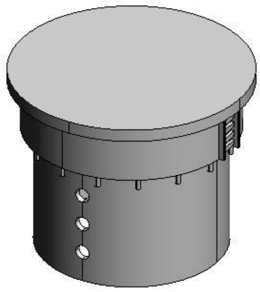
The concept design for the support structure consists of 4 vertically aligned Leg Support assemblies which are connected via 4 Support Rod and Clamps. Each Support Leg is fixed in place by a large Screw that penetrates the ground.



Support Leg Assembly

No	Component Name
1	Top Grid Piece
2	Generic Grid Piece (2m)
3	Initial Grid Piece
4	Foot Assembly

1. Top Grid Piece


Top Grid Piece

The Top Grid Piece, as the name suggests, is the final piece of the Support Leg. The main function of this component is to prevent the Hoists from elevating too far and falling off the Leg Support. In later iterations the Top grid Piece will also feature sensors that are capable of sensing when the Support Leg has deflected beyond tolerance, to prevent the misalignment ruining the print.

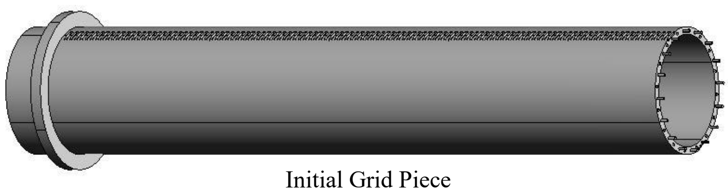
2. Generic Grid Piece (2m)


Generic Grid Piece

The Generic Grid Piece is the variable element of the Support Leg. To extend the maximum height of the SALEM Printer more of these parts can be added to each Leg Support. All grid Pieces feature 2 tracks running parallel along the component for the Hoist Track Gears to engage with and react off allowing them to traverse along the Support Leg length safely and in a controlled manner. The concept design has this piece at 2m in length, however there is no technical or practical reason why this element cannot come in several different size variants to provide better customizability of the SALEM Printer.

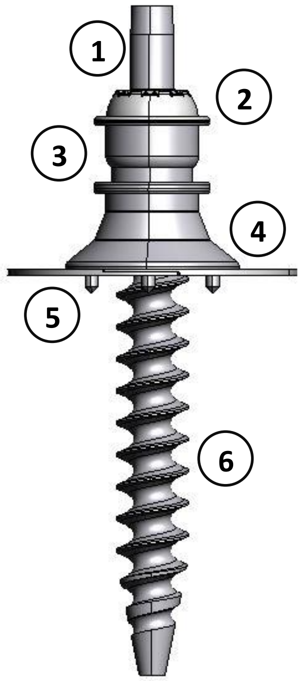
3. Initial Grid Piece

The Initial Grid Piece is the first segment of the Support Leg Track. This component differs to the Generic Grid pieces as it has a stop feature at the bottom to prevent the Hoists from travelling too far down and clashing with the Foot Assembly.


Initial Grid Piece

2.4.2 4. Foot Sub-Assembly

The Foot Assembly provides a platform for the Track Grid to be erected on and contains the necessary architecture to align the Support Leg to true vertical via a Pivot Joint. The Foot Sub-Assembly is made up of several components:



Annotated Foot Assembly

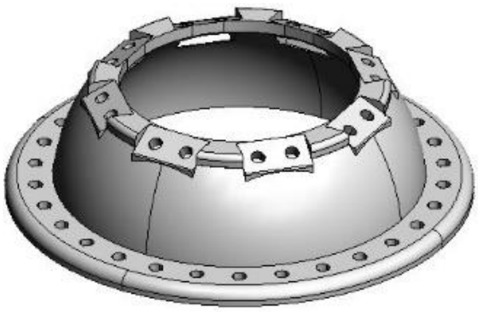
No	Component Name
1	Pivot Joint
2	Pivot Joint Top Housing
3	Pivot Joint Bottom Housing
4	Foot Sole
5	Weight Distribution Plate
6	Ground Screw

1. Pivot Joint

The Pivot Joint is a ball joint that allows the Support Leg to be deployed on uneven ground and adjusted to align vertically. The concept design allows for up to 15 degrees of correction to the angle of the Support Leg.


Pivot Joint

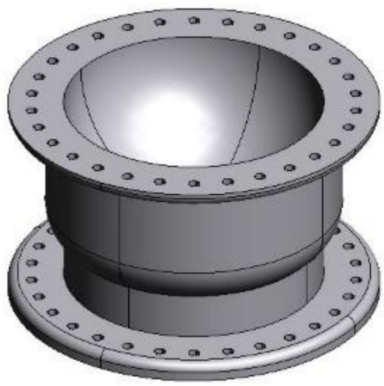
2. Pivot Joint Top Housing


Pivot Joint Top Housing

The purpose of the Pivot Joint Top Housing is to contain and fix the Ball Joint into place once correctly aligned. It secures the Ball Joint by applying torque to a set of 8 abradable pads that react off the Housing onto the Ball Joint. There is a risk that this method of locking the Pivot will not be suffice for larger Print Projects due to forces during operation causing gradual slippage of alignment. This should be addressed during design analysis and the concept may need altering in later iterations for a more sophisticated locking feature.

3. Pivot Joint Bottom Housing

This component is the Bottom half of the Pivot Ball Joint Housing. In later iterations of the design the Pivot Joint Bottom Housing should feature a system of motorised rollers and sensors that allow the Pivot Ball to be automatically calibrated.

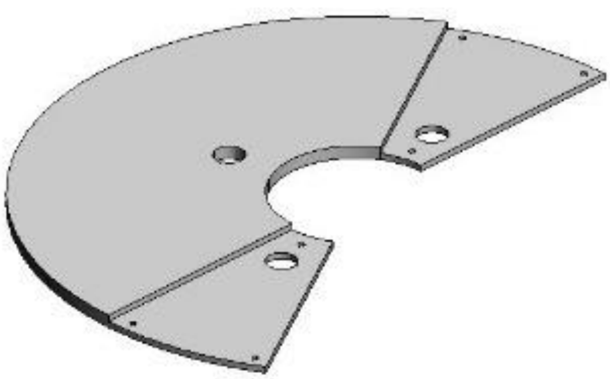

Pivot Joint Bottom Housing

4. Foot Sole

The Foot Sole is the ground interface of the Leg Support and houses the Ground Screw. This component features 4 studs that lock into the Weight Distribution Plates and penetrate the ground to provide purchase for torqueing the Ground Screw.

Foot Sole

5. Weight Distribution Plate



Weight Distribution Plate

The Weight Distribution Plates are used to distribute the Force applied by the Ground Screw evenly to the ground to prevent the Foot Sole sinking into the ground when fully torqued. The Plates have been designed in halves to make transportation and assembly easier.

6. Ground Screw

The Ground Screw is responsible for securing the Support Leg in position by clamping the Foot Sole to the ground. The Ground Screw should be capable of fixing the Support Leg to the Ground with enough force to prevent any passive deflection. Later iterations of the SALEM printer design may see this feature dismissed as unnecessary if analysis shows that the printer is stable enough without such a fixture.

Ground Screw

Support Rods & Clamps

The Support Rods and Clamps connect all four Support Legs to one another, providing additional rigidity to the Support Structure. This is an early design and intended to demonstrate the overall concept only. In later design iterations the Support Rods will be defined into modular segments like the Support Leg Grid Pieces to allow for a variable print envelope. Some form of Rod length adjustment feature will also be necessary to allow fine tuning of Rod length.

Support Rod & Clamp Assembly

2.4.3 Weight

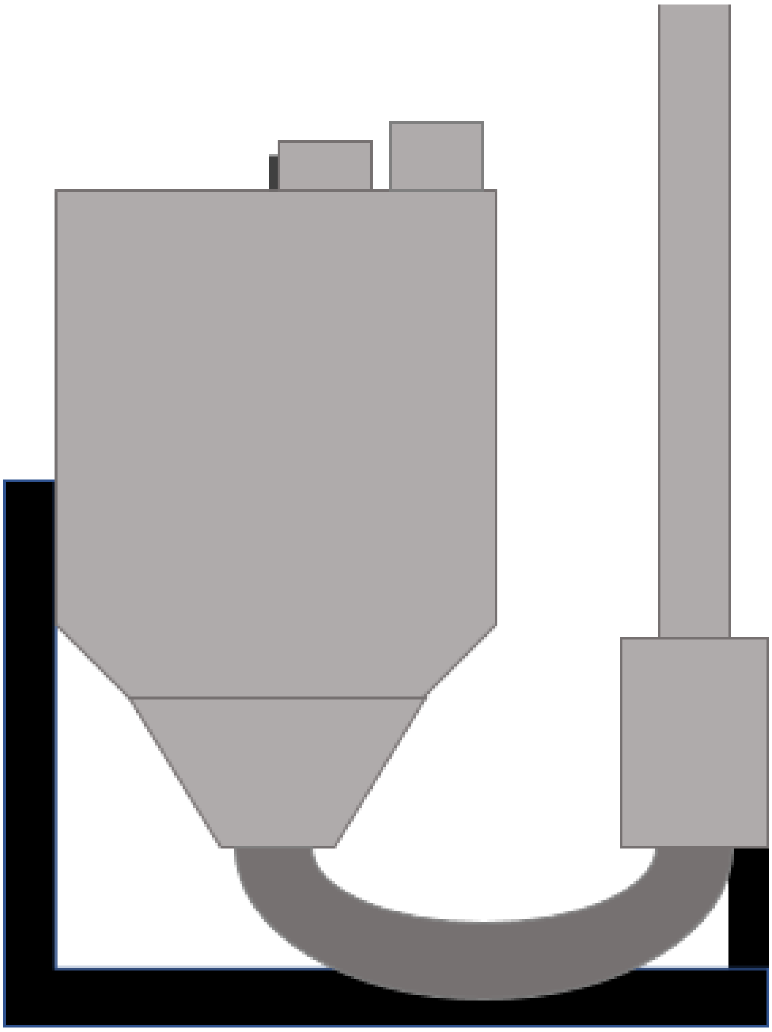
The concept design for the Support Structure currently presents some significant challenges in regard to weight to meet requirements. Two major components are above the 2-person manual handling weight limit by a large degree. The Foot Sole Concept weighs in at approx. 63Kg which is around 50% heavier than requirements. The Current model for this component has been designed to have a very high factor of safety and is wholesale much thicker than is perhaps required. In later iterations the weight could be reduced by optimising and reducing wall thickness as, in some areas this is several centimetres thick and is unlikely to be required to be this thick. Alternatively, internal cavities could be designed into the Foot piece to remove unnecessary material, but this would potentially require the component to be 3D printed, drastically increasing the cost of manufacture.

The ground screw presents the biggest weight challenge of the entire Printer with the current design weighing over 125kg, 3 times requirement. The assumption is that this component would be manufactured out of Titanium, however, if a lighter material such as Aluminium was used instead the mass of the component could drop to around 80kg. Aluminium does not have as desirable mechanical properties as Titanium though, and switching may increase the likelihood of failure of the component. Other options to reduce weight include reducing the head thickness of the Screw, Increasing the internal bore diameter and depth or reducing the entire scale of the Screw. Shrinking the scale of the ground screw may have detrimental effects to the rigidity of the Leg Supports however, which could increase deflection and likelihood of collapse.

Support Structure (5x5x5m) Concept Weight Assessment					
Part Name	**QTY**	**Material**	**Estimate Type**	**Mass (Kg)**	**Total Mass (Kg)**
Ground Screw	4	Titanium	Initial CAD	125.65	502.6
Weight Distribution Plate	8	Titanium	Initial CAD	19.57	156.56
Foot Sole	4	Aluminium	Initial CAD	62.94	251.76
Pivot Joint Bottom Housing	4	Aluminium	Initial CAD	31.90	127.6
Pivot Joint	4	Titanium	Initial CAD	32.85	131.4
Foot Pivot Joint Top	4	Aluminium	Initial CAD	6.60	26.4
Bottom Grid Piece	4	Aluminium	Initial CAD	13.76	55.04
2m Grid Piece	8	Aluminium	Initial CAD	28.42	227.36
Top Grid Piece	4	Aluminium	Initial CAD	1.97	7.88
Support Clamp	8	Aluminium	Initial CAD	1.18	9.44
Support Rod	4	Aluminium	Initial CAD	5.31	21.24
M12 50 Bolt and Nut	352	C.Steel	Calculation	0.063	22.32
M6 40 Bolt	64	C.Steel	Calculation	0.091	5.82
Pivot Ball Abrasion Pads	32	Ceramic	Allowance	0.05	1.6
Sensors	1	Mix (Light)	Allowance	2	2
Electrical Details	1	Mix (Light)	Allowance	4	4
Total Support Structure Weight				**336.4Kg**	**1,553 Kg**

For snapshots of the CAD model material properties, see **Appendix 2 – Material Mass Properties**

2.5.0 Cement System



Representation of the Cement Delivery System

2.5.1 Requirements

Functionality

The Cement Delivery System is intended to provide a continuous and variable feed of wet cement to the Extruder during print. In this endeavour it must be capable of maintaining a constant differential head that is higher than the print envelope. As the print envelope is relative and will drastically change dependent on the intended print, the Cement Delivery System must be capable of maintaining and manipulating the system pressure for a differential head of between 2m and 60m. The delivery system must also maintain a high enough pressure to counteract the losses caused by the viscosity of the cement.

The system must feature a mixing tank that constantly rotates to prevent premature setting of the cement and as the SALEM Printer is intended for use in extremely cold environments such as Mars, it is essential that the Cement System can maintain a stable temperature self-sufficiently. To prevent the need for continuous print pauses, the system must feature a Cement Tank that is capable of being refilled in use and can contain enough cement at any given time for at least 2 hours operation.

Assembly & Weight

To ensure on-site assembly is possible, all elements of the SALEM Printer must weigh less than the 2-person manual handling limit. For applications on Earth and in locations with good access, it is permissible for the Cement Delivery system to be delivered as a full assembly to reduce setup time of the printer, however for off-grid use, the Cement System will be delivered to location in parts and assembled on site. It must be possible to fully assemble and calibrate/check the SALEM Cement Delivery System in 1 day, so should be designed with minimal components and easy to assemble interfaces. The Cement System should also be possible to assemble with only standard hand tools.

The SALEM Printer will potentially be deployed in extremely remote locations which will increase the difficulty of preparing the site before print. For this reason, the Cement System must be mountable on uneven and uncertain grounding.

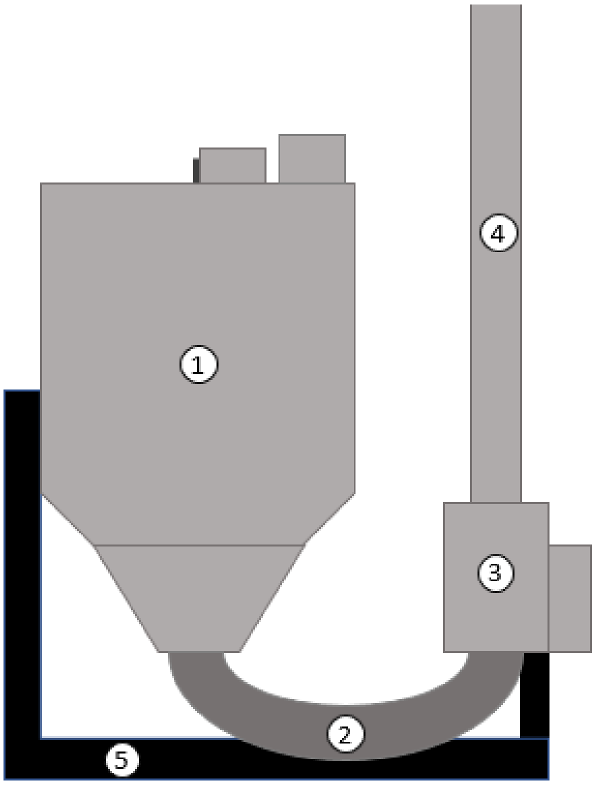
Safety & Quality

If the Hose, Extruder or Cement Pump jam during operation the Cement System must recognise the fault and pause operation. The Cement System must be able to withstand extreme weather such as temperature drops, dust storms etc without significant wear and have protection against solar radiation.

Cement System Requirements Summary

Requirement	Type
Must be able to create a differential head of at least 60m	Functionality
Must be able to control and manipulate system pressure dynamically	Functionality
Tank must rotate supply cement during operation	Functionality
Must be able to maintain a constant pressure of 100 PSI	Functionality
Must be operable between -200 and 120 degrees F	Functionality
Tank must have at least a $17.3m^3$ cement capacity	Functionality
Must be refillable during operation	Functionality
All components must weigh less than 44Kg	Assy & Weight
Must be able to assemble in less than 24 hours	Assy & Weight
Should be possible to assemble with only hand tools	Assy & Weight
Must be mountable on uneven and uncertain grounding	Assy & Weight
Must automatically detect a jam and pause print	Safety & Quality
Should resist all Extreme weather scenarios	Safety & Quality

2.5.2 Cement Delivery System Concept Design



No	Component Name
1	Tank
2	Connection Hose
3	Pump
4	Delivery Hose
5	Stand

Annotated Cement Delivery System Concept

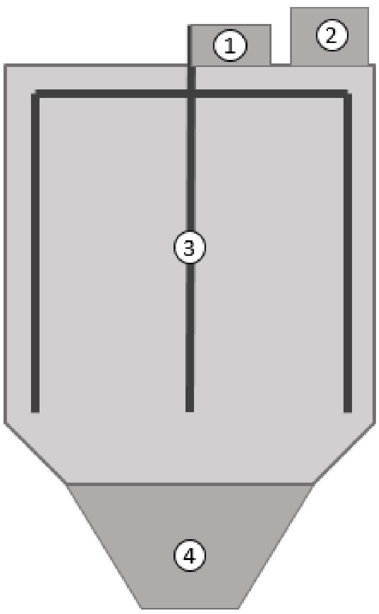
The Cement Delivery System is the SALEM Printer module that is responsible for delivering the cement to the Extruder in a controlled, consistent manner. The design for this element is still in an extremely early phase and the following description represents a basic solution only and not a comprehensive design study. The current concept design consists of a Tank to store and rotate the wet cement, a Pump to pressurise the cement and deliver to Extruder, a Stand and two Hoses for directing the cement.

Tank Sub-Assembly

The concept Cement Tank is an upright, thin walled, stainless steel vessel that tapers at the bottom (4) to gravity feed the cement to the Pump. There is an entry point (2) that allows the Tank to be topped up during operation to prevent the need for unnecessary print pauses.

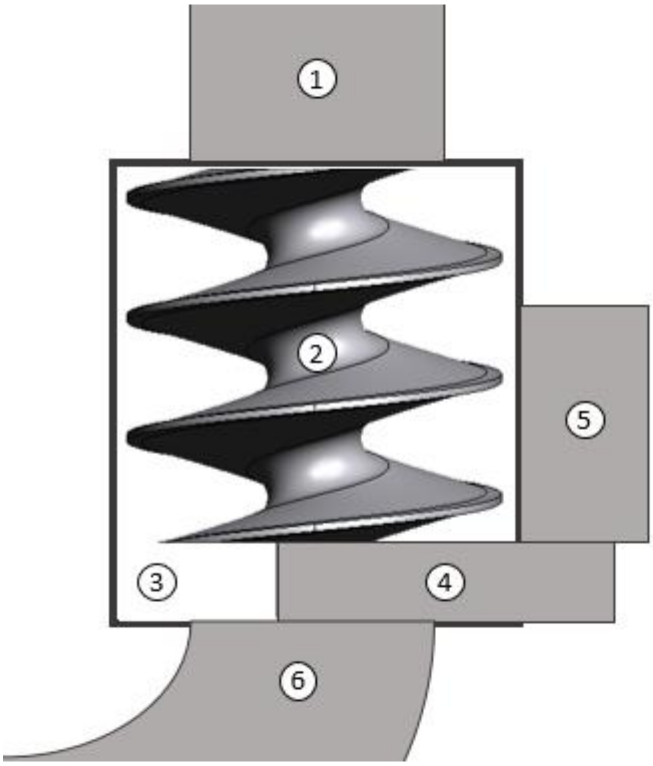
Inside the Tank is a 4-pronged whisk like feature (3) that, coupled with a Motor (1) constantly mixes and turns the cement to prevent premature setting. This part of the Cement Delivery System may be pre-assembled before arrival on site, although this is entirely dependent on weight and application. If the sub-assembly weighs more than 44kg it may be necessary to deliver the Tank in parts to locations where overhead cranage is not an easy option, such as Mars.

The initial design assumes the tank will have a diameter of 3m and a height of 4m for a volume of $28.27m^3$ putting the tank capacity well above the requirement of $17.3m^3$.



Annotated Cement Tank Concept

Pump Sub-Assembly



Annotated Cement Pump Concept

No	Component Name
1	Delivery Hose
2	Pump Screw
3	Pump Housing
4	Pump Screw Drive Chain
5	Pump Screw Motor
6	Connection Hose

The Cement Delivery System Pump pressurises the system and delivers the cement to the Extruder. Like the Extruder Pump, the concept Cement Delivery Pump utilises the rotation of a screw to force the movement of the cement. Just like the Extruder, the pump features a Pump Screw (2), Drive Chain (4) and Motor (5) to control the flow of cement, however as this pump is not just for controlling the flow of the cement but also pressurising the system, the power requirements will be much higher than the Extruder Pump.

The intent is to deliver the Cement Pump to site as a sub-assembly to reduce assembly time and complexity. If we assume that the Screw Pump will have roughly the same dimensions as the Extruder Screw Pump, then this sub-assembly should be well within the manual handling limits for a two-person lift.

Support and Hoses

Some form of stand will likely be required for supporting the cement system during operation. This stand needs to be capable of adjustments to allow for deployment on uneven grounding and should be as lightweight as possible, weighing no more than 44kg to ensure a manual lift is possible. As this Support Stand will be a static feature with few interfaces it should be possible to form out of aluminium or other lightweight metals/ composites.

The final element of the Cement Delivery Concept is Hoses that connect the Tank, Pump and Extruder together. These hoses will be made of a flexible material and will feature a heated internal mesh to prevent the cement from freezing in extreme climates. Two hoses will be required. One that connects the Tank to the Cement Pump, and a second that links the Cement Pump to the Extruder. The Delivery Hose will come in a variety of lengths to suit the demands of the respective print.

2.5.3 Weight

As the concept design for the Cement Delivery System is still in its earliest stages, an exact assessment on weight cannot yet be complete, however we can make a rough approximation based on the anticipated mass of each of the components.

Cement System Concept Weight Assessment				
Part Name	**QTY**	**Material**	**Estimate Type**	**Mass (Kg)**
Screw Pump	1	Titanium	Initial CAD	11.88
Screw Pump Drive Housing	1	Aluminium	Initial CAD	0.90
Screw Pump Drive Chain	1	Steel	Allowance	0.50
Screw Pump Motor	1	Mix (Heavy)	Allowance	8.00
Pump Housing	1	Aluminium	Allowance	8.00
Connection Hose	1	Mix (Light)	Allowance	5.00
Delivery Hose (10m)	1	Mix (Light)	Allowance	20.00
Support Stand	1	Aluminium	Allowance	25.00
Tank Shell	1	Stainless Steel	Allowance	20.00
Mixing Arm	1	Titanium	Allowance	18.00
Mixing Arm Motor	1	Mix (Heavy)	Allowance	8.00
12M 40 Bolt & Nut	12	C. Steel	Calculation	0.52
Electrical Details	1	Mix (Light)	Allowance	4.00
Total Extruder Assembly Weight (Dry)				**129.8 Kg**

This initial assessment suggests that for a two-person assembly to be possible, the Cement Delivery System must be broken down into at least three sub-assemblies. Rationally, this could be broken down as: Pump Sub-Assembly (~30 kg), Tank Sub-Assembly (~50 kg) and the Support Stand (~25 kg) and Hoses (~25 kg) as loose parts. As the current design provides a Tank volume of $28.27m^3$, which is about $11m^3$ more than the specified requirement, it may be permissible to reduce the weight of the module by scaling the whole assembly down. The consequence of doing this would be a reduced capacity, meaning more frequent top ups of cement into the Tank to print.

2.6.0 Power & Control System

2.6.1 Requirements

Functionality

The control systems function is to electronically manage the SALEM Printer operation. The control system must be capable of converting 3-Dimensional Cartesian coordinates into a print sequence in a relative print envelope. It must be able to triangulate the relative location of the Extruder based only on the extension length of the Hoist Cables and the distance between Hoists but should have some secondary means of determining these parameters for safety. If the two measurements misalign past a certain tolerance the Printer should pause for inspections and/or maintenance.

The software must also be capable of maintaining a steady temperature for the printer to function in extremely cold conditions. This would require temperature inputs from at least the Cement System and the Extruder heating systems, plus ambient temperature. The Control System will also manipulate the cement flow and diameter with inputs from the Cement Tanks and feed Pump, Extruder Screw Pump and Nozzle Actuators. The software must be able to map the landscape geometry using sensory input from the Extruder and cable length extensions from the Hoists in order to lay a foundational layer to print the structure on. This will enable printing structures on any terrain without needing to prepare the land first. The Control System should also aid in assembly and calibration of the Printer so the software must feature manual control of individual printer modules and should feature automatic settings for certain assembly manoeuvres such as lifting Grid Pieces and calibration.

The print must be operable with a battery source and Solar Array continually for at least 8 hours. This is to ensure operation is practical in remote locations such as Mars. For suburban and urban applications, the SALEM Print should be able to interface with standard mains supply.

Calibration

As the only fixed references are the four Leg Supports, everything else about the print envelope must be determinable by the printer through reference point calibrations. The software should create a virtual print envelope in which absolute coordinates are converted to relative cable extensions and to prevent the Printer from trying to print outside of the print envelope.

Safety & Quality

A key success indicator for the SALEM Printer is that it operates safely and with little maintenance. To do this the Printer should utilise as much data as possible to recognise a fault before it becomes an issue. When the SALEM Printer is in print, the software must be capable of recognising when a misalignment is about to occur and pause the print for inspection. It should also recognise when an earthquake or other natural phenomena is taking place and return the Hoists to ground height.

The Hoists are used to lift people for a 2-person assembly, generating a risk of falling. To reduce this risk the Software must recognise when a Hoist is slipping and activate a secondary braking method. There should also be a secondary safety brake on the Hoist Spools that are activated if the motor passes a certain torque or surges. If a cable snaps the Printer must be able to minimise Extruder disturbance by compensating with the other Hoists.

Physical

The SALEM Printer is intended to be used in an array of extreme environments such as Mars and Antarctica so all elements of the printer must have protection from temperature and pressure fluctuations, solar radiation and fine particulates. The Control System should maintain optimal temperature through fans and heating elements. In terms of size and ease of use, the Control System Console should be easily handled by one person and, ideally, wirelessly controlled to allow operations on Mars from the comfort and safety of a previously constructed structure. The Console must be able to interface with the power source and the Printer with easy modification of connection plugs to allow for changes to power source. The SALEM Printer should also have a configuration that allows for production and storage of energy self-sufficiently. The printer should therefore feature a solar array and battery option.

Power & Control System Requirements Summary

Requirement	Type
Must be able to calculate and map 3D coordinates from Hoist Cable Extension lengths.	Functionality
Must be able to calculate relative shape and size of the print envelope based on cable lengths	Functionality
Should have a secondary data input for Hoist and Extruder locations	Functionality
Must stop if it receives conflicting information from the primary and secondary sensors	Functionality
Must maintain a steady temperature across the Cement System and Extruder.	Functionality
Should maintain a steady temperature across all Printer modules.	Functionality
Must control Cement Flow Rate	Functionality
Must control Cement Extrusion diameter	Functionality
Must be able to map ground geometry and execute a foundation print	Functionality
Must feature manual control for Hoist, Leg support and Extruder modules	Functionality
Should feature automatic settings for key manoeuvres	Functionality
Must Calibrate Hoist locations	Calibration
Must Calibrate Hoist Cable Lengths	Calibration
Must Calibrate Print Envelope	Calibration
Must pause print if primary and secondary measurements exceed 2% misalignment.	Safety & Quality
Must retract Hoists to ground in the event of a natural phenomenon.	Safety & Quality
Must recognise Hoist Slippage and engage secondary brake.	Safety & Quality
Should instantly compensate for a snapped cable with the remaining Hoists.	Safety & Quality
Must be protected from the effects of Solar radiation	Physical
Must be resistant to pressure fluctuations	Physical
Must maintain optimal working temperature independently	Physical
Console and Console Cables should weigh less than 44kg	Physical
Should have easy to modify connection ports between power source, console and printer	Physical

2.6.2 Power & Control System Concept

2.6.2 Battery Pack

Fig 7: Tesla Powerwall

13.5Kwh Tesla Powerwall Cell

The Battery pack is conceptualised as an array of Tesla Powerwall Cells that, in conjunction with the Solar Array, provide the SALEM Printer with all its energy requirements. The Battery pack is an optional feature to allow use of the printer in remote off-grid locations.

The Battery Pack is intended to maintain power to the printer during night-time hours and during daytime the printer will predominantly be powered by the Solar Array. The Printer should be capable of 8 hours continuous full power operation on battery power alone and a single Tesla Powerpack is rated at 13.5Kwh. In **Appendix 1 – Printer Energy Consumption & Production** we calculate that the SALEM Printer will use 7.362Kw/h of full power use. Therefore:

$$No\ of\ Powerwalls = \frac{Time \times Power}{Power\ Rate}$$

$$No\ of\ Powerwalls = \frac{8 \times 7.362}{13.5} = 4.363\ Cells$$

If we round up to 5 cells, we can transform the formula to determine the maximum operation time on a full charge:

$$Time\ (hrs) = \frac{No\ cells \times Power\ Rate}{Power}$$

$$Time = \frac{5 \times 13.5}{7.362} = 9.17\ Hours$$

Tesla specifies that each Powerwall cell weighs 97Kg. This means the total Battery weight would be approx. 485Kg for a 5-cell battery pack.

2.6.2 Solar Array

Fig 8: Desert Sunlight Solar Farm

Image of the Desert Sunlight Solar Farm

The solar array is a lightweight, durable, flexible Polycrystalline photovoltaic array that will be used to power the primary daylight operation of the SALEM Printer in off-grid locations such as Mars as well as charge the Powerwall battery pack for continued operation through the night. This is another feature that is optional for most Earth based print applications and is predominantly aimed as a solution to printing on Mars.

The Solar Array needs to be light, to allow shipping to Mars and must require no more than 24 hours to assembly and begin using. A flexible material is preferred for the Solar Panels to allow the array to be packed up and moved from one print location to another.

In **Appendix 1** we calculate the total energy power rate of the SALEM printer to be 7.362Kwh. if we assume the power of the printer never exceeds 7.5Kwh, we can find the total area of the Solar Panel array to produce the energy we need. We know that each Tesla solar tile can produce up to 12w of energy and with that can find the number of cells required by dividing the required power rate, by the individual cell power rate:

$$No\ Cells = \frac{SALEM\ Power\ Rate}{Cell\ Power\ Rate}$$

$$No\ Cells = \frac{7500}{12} = 625$$

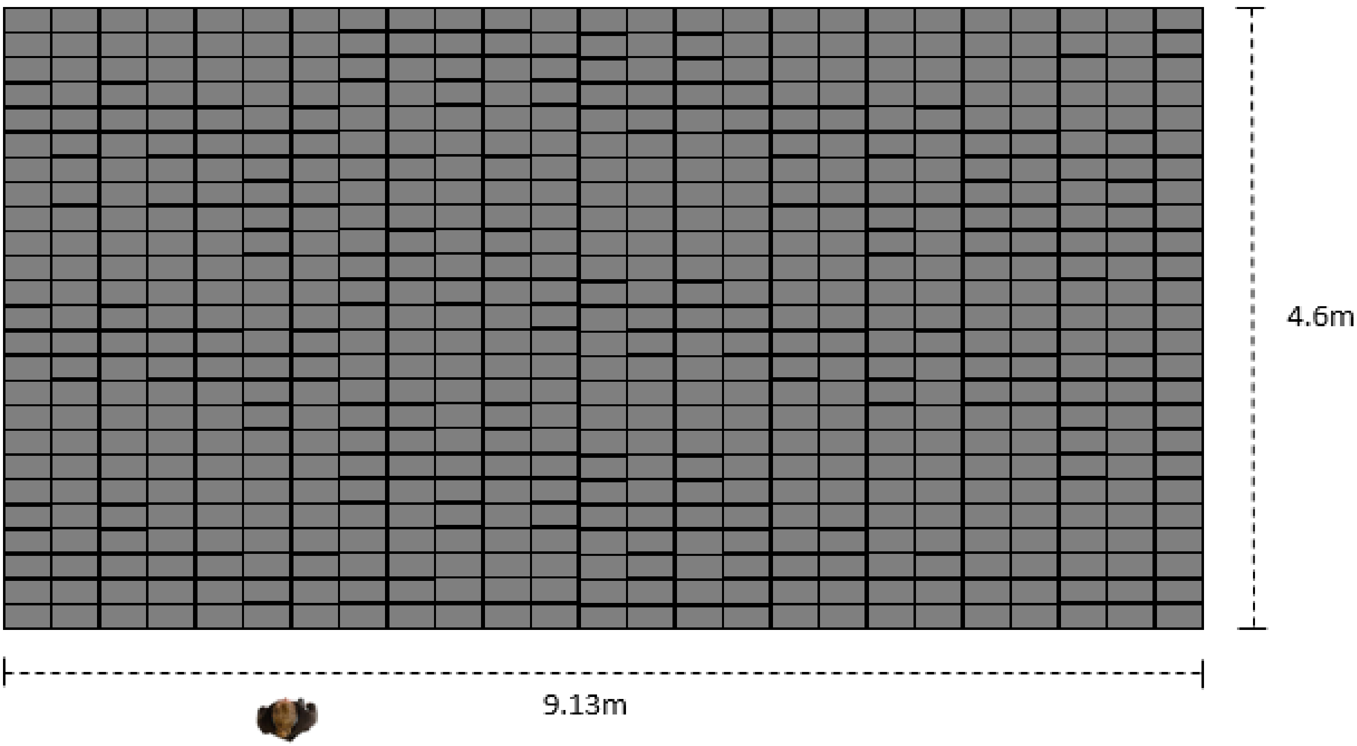
Assuming there is 12 hours of optimal sunlight, this number of Solar cells, in conjunction with the Powerwall battery would enable up to 21 hours of optimal printing per day, off-grid.

If we want to know the size of our solar array in a square arrangement, we take the square root of the number of cells and multiple by the width and length to find the width and length of the array. We know that the Tesla Solar tile has the dimensions:

Length = 365mm
Width = 184mm

So, for width and length of our array we can say:

$$Array\ Width = \sqrt{No\ Cells}\ \times Cell\ Width$$
$$Array\ Width = \sqrt{625}\ \times 0.184 = \mathbf{4.6m}$$
$$Array\ Length = \sqrt{No\ Cells}\ \times Cell\ Length$$
$$Array\ Length = \sqrt{625}\ \times 0.365 = \mathbf{9.13m}$$



Representation of SALEM Solar Array for size reference

For a flexible 10W Polycrystalline Solar Cell we can expect a weight of 267g [8]. If we scale up for 12W we can say a single cell weighs approx. 320g. We can now determine the total mass of the Solar Array with the following formula:

$$Cell\ weight \times No\ Cells = Package\ weight$$
$$320 \times 625 = 200{,}000g = \mathbf{200Kg}$$

2.6.2 Console

The Console is the heart of the Control System and is intended to be used to create models and mesh files and execute these files by controlling the operation of the SALEM Printer. The Console should function and look as much like a laptop as possible and for the most part, the requirements of the Console can be fulfilled with a standard laptop. The Console however, needs to withstand extreme temperature fluctuations and therefore must feature some form of heating element. The console will feature an array of connection ports and will be designed for easy modular replacement of parts.

With the use of signal relays and wireless technology such as Bluetooth and WIFI it would be possible to operate the SALEM Printer from a remote location allowing operators on Mars to construct new 3D structures from the comfort and safety of a shelter. This would also allow more prints to be operated by the same crew freeing up more resource for other matters.

The weight of the console would be approximately the weight of a standard engineering laptop plus the heating element. For our evaluation we will assume this is approximately equal to 10kg. If we also factor in an allowance for cables, connectors and single relays we can estimate that the console package weight would be in the region of 40Kg

2.6.3 Weight

If we assume the SALEM Printer is intended to be used for off-grid applications and therefore requires a Battery Pack and Solar Array, then the Power and Control System total weight is:

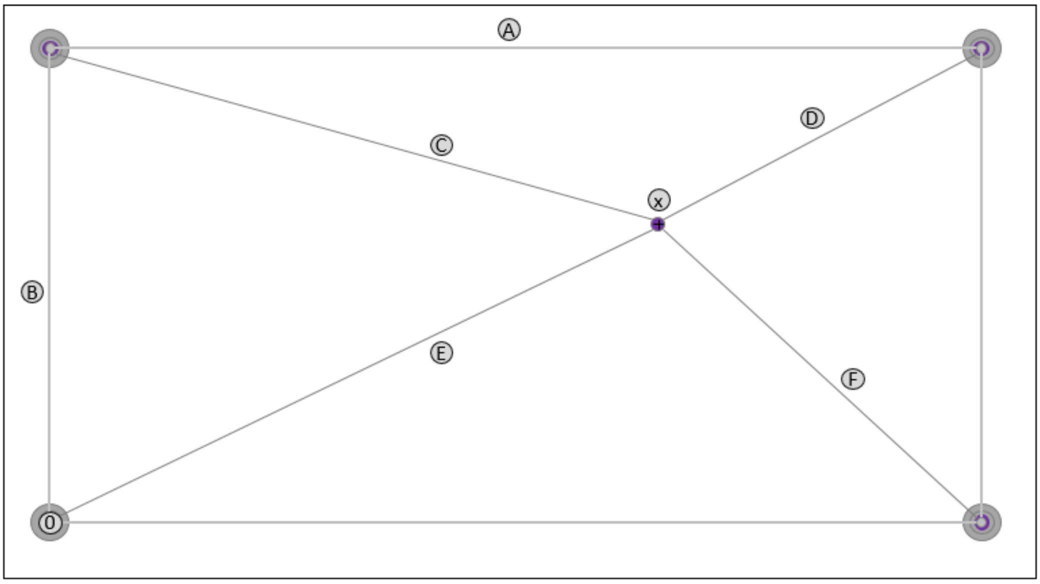
Item	Weight (Kg)	Estimate Type
Console & Console Cables	40	Allowance
Powerwall Battery	485	Reference
Solar Array	200	Calculation
Total	**725Kg**	

The weight of the Power and Control System is ultimately dependant on the printing requirements. It would be possible to operate the SALEM Printer off-grid with just one Powerwall cell and a Solar Array of $2m^2$ or less if a slower print speed is optional. In this fashion the weight of the Power and Control System could be reduced to approx. 200Kg at a print speed of 0.1m/s. This may ultimately prove fast enough for practical use on Mars because of the time benefits we gain from the variable Extruder Nozzle minimising travel distance to complete a print.

2.6.4 Calculating Cartesian Coordinates Proof of Concept

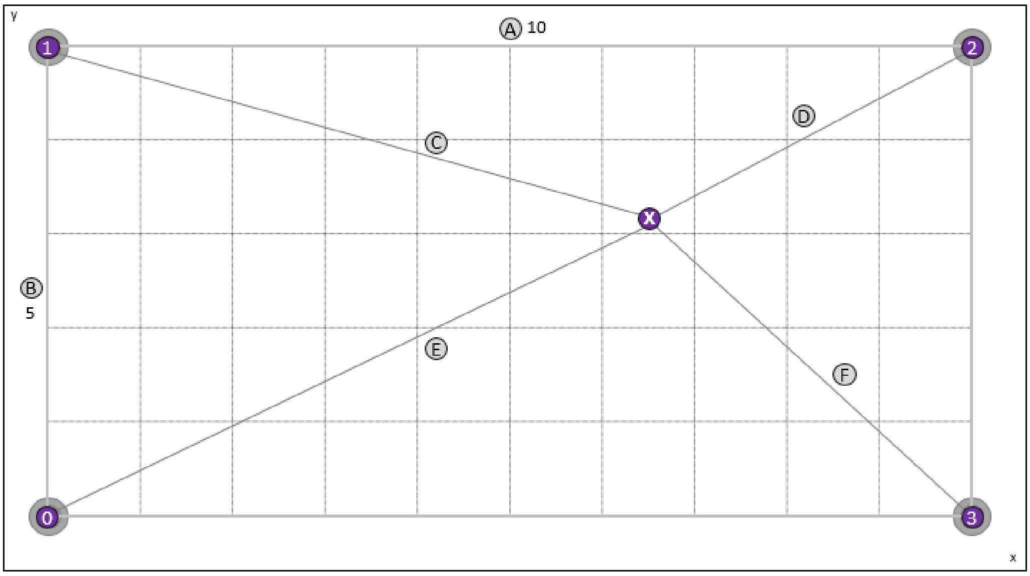
2.6.4 Right Angle Print Envelope

The Software for the SALEM Printer must be able to control the Extruder within an entirely relative print envelope, so will require inputs from the Hoists, about cable extension lengths, and measurements of distances from points in order to translate this into an accurate Cartesian Grid. The SALEM Printer has 8 Hoists that interject at the Extruder. The top four Hoists are intended to maintain the Z Axis (height) and the bottom four Hoists manipulate the 2-Dimensional profile (X & Y Axis). If we ignore the top four hoists for now and view the print envelope from the top down, we find that the Cables form four triangles:



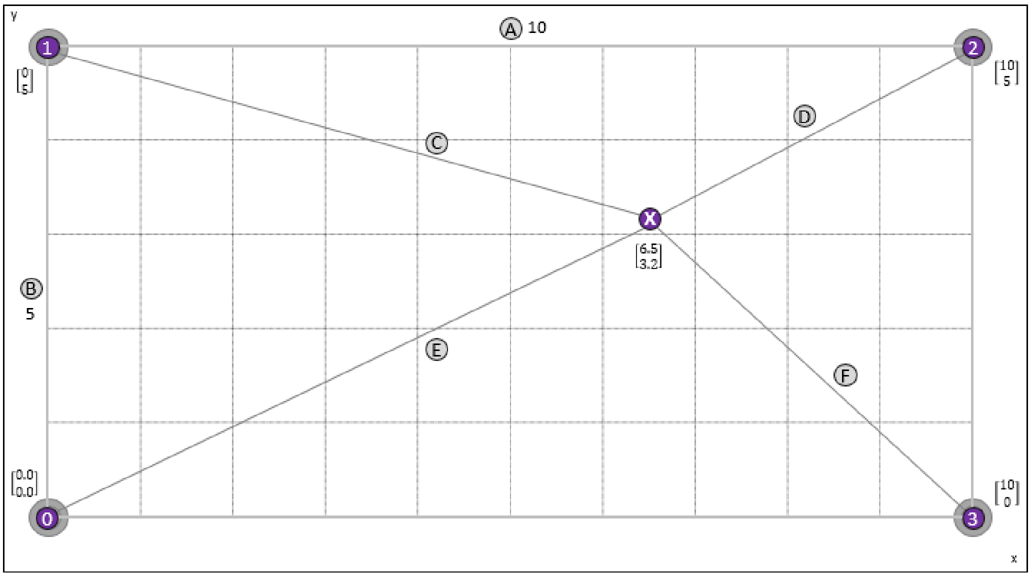
Annotated Top View of SALEM Print Envelope: Image 1

In a perfect Right-Angle Print Envelope, it is possible to calculate Hoist cable extension lengths if we are given the Print Envelope size and shape. In our example the print envelope has the length A = 10 and Width B = 5.



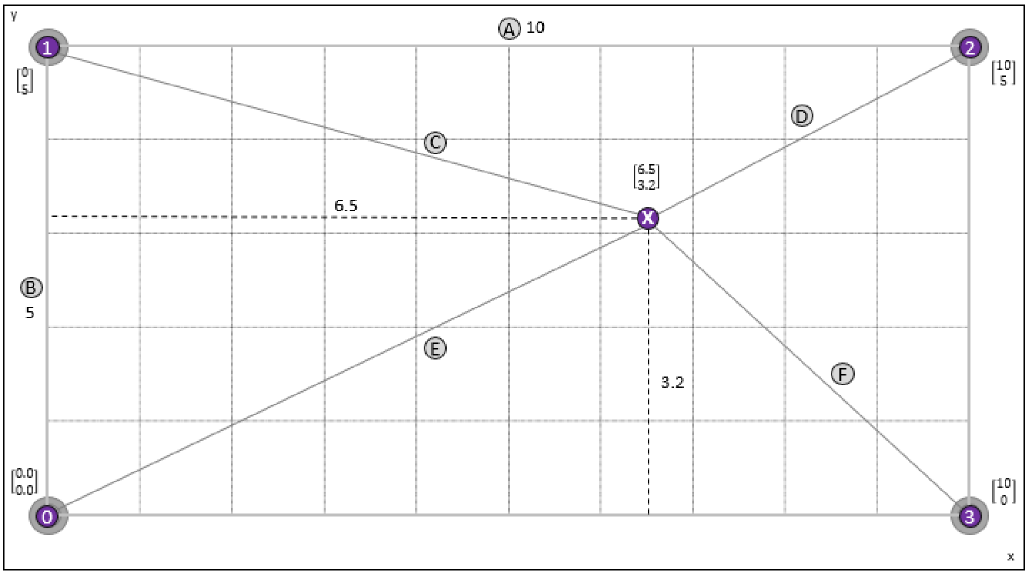
Annotated Top View of SALEM Print Envelope: Image 2

If we take a reference point at Point 0 and use this location as our datum for 0, we can express the locations of all Hoists as vectors in a grid.



Annotated Top View of SALEM Print Envelope: Image 3

In our example x can be expressed as the vector $\begin{bmatrix} 6.5 \\ 3.2 \end{bmatrix}$. This means that it is 6.5 units away from Point 0 in the x direction and 3.2 units away from Point 0 in the y direction. If we draw this as a right-angle Triangle, we can use Pythagoras' Theorem $a = \sqrt{b^2 + c^2}$ to find length *E*.

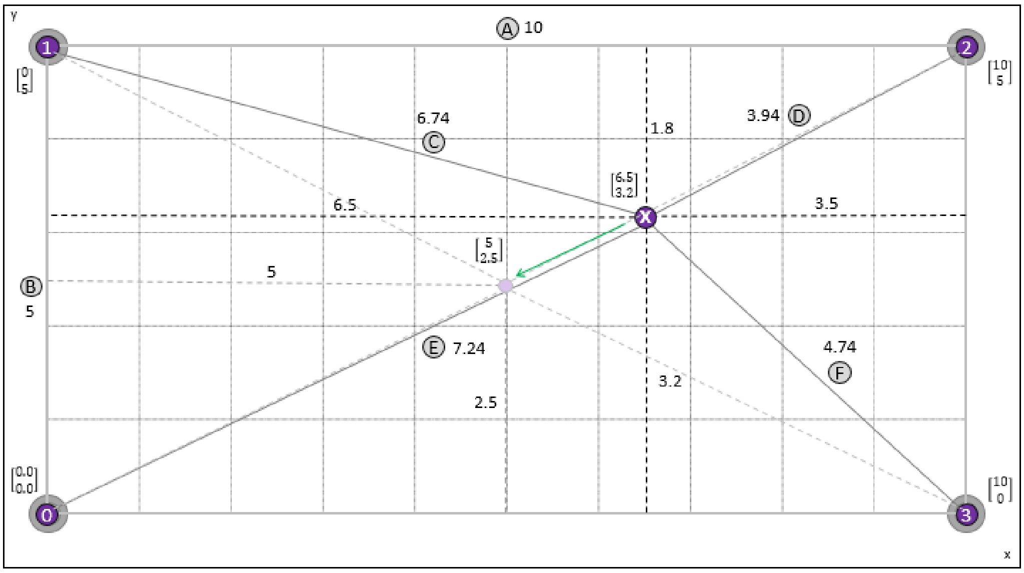


Annotated Top View of SALEM Print Envelope: Image 4

For our example to find *E*:

$$E = \sqrt{3.2^2 + 6.5^2} = 7.245$$

This method can be repeated to find the lengths of *C, D* and *F*



Annotated Top View of SALEM Print Envelope: Image 5

To calculate cable lengths from coordinates we can rearrange the formula as:

$$Cable\ Length = \sqrt{(x_{Hoist} - x_{Extruder})^2 + (y_{Hoist} - y_{Extruder})^2}$$
$$C_l = \sqrt{(x_H - x_E)^2 + (y_H - y_E)^2}$$

Where:

- C_l is cable length
- x_H is the x axis coordinate of the Hoist Point
- x_E is the x axis coordinate of the Extruder
- y_H is the y axis coordinate of the Hoist Point
- y_E is the y axis coordinate of the Extruder

For example, if we want to find length *D*:

$$D = \sqrt{(10 - 6.5)^2 + (5 - 3.2)^2} = 3.94$$

If we want to traverse from vector $\begin{bmatrix} 6.5 \\ 3.2 \end{bmatrix}$ to $\begin{bmatrix} 5 \\ 2.5 \end{bmatrix}$ in 2 seconds we solve the required cable lengths for both vectors and compare them to find the length change. That length change is then divided by time, to work out the cable retraction/extension speed:

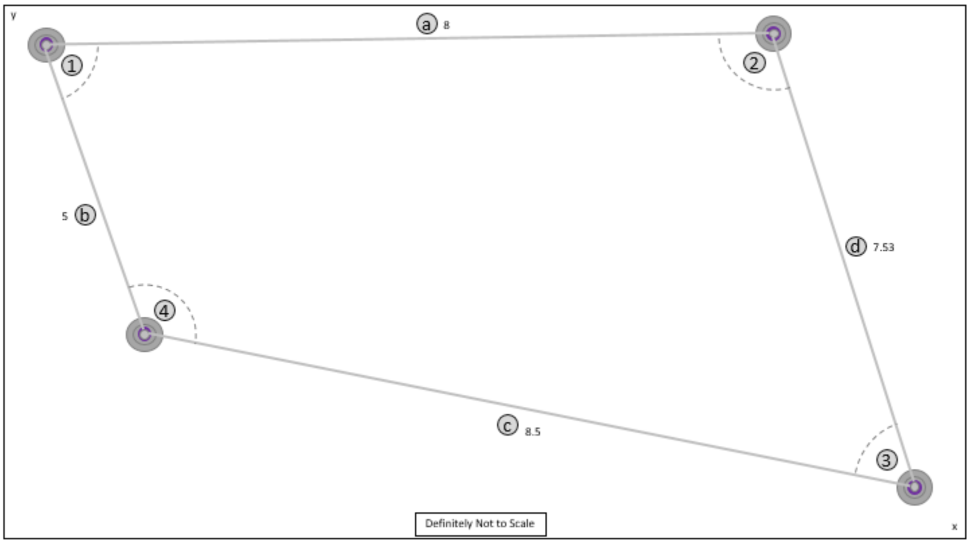
$$Speed = \frac{Cable\ length\ change}{time}$$

Pos.	Point X		Cable Lengths				Speed (m/s)			2
			Cl=√((x1-x2)^2+(y1-y2)^2)				(Cl1-Cl2)/T			
	X	y	E	C	D	F	E	C	D	F
1	6.5	3.2	7.24	6.74	3.94	4.74	0.00	0.00	0.00	0.00
2	5	2.5	5.59	5.59	5.59	5.59	-0.83	-0.58	0.83	0.42

E and *C* are negative because both cables are retracting in this manoeuvre. With this information it is possible to programme the SALEM Printer to locate and manipulate the Extruder anywhere within the Print Envelope by using Pythagoras' Theorem and a Cartesian grid. The same logic can be applied to find the Hoist cable extension/retraction speeds and lengths for the Z axis Hoists.

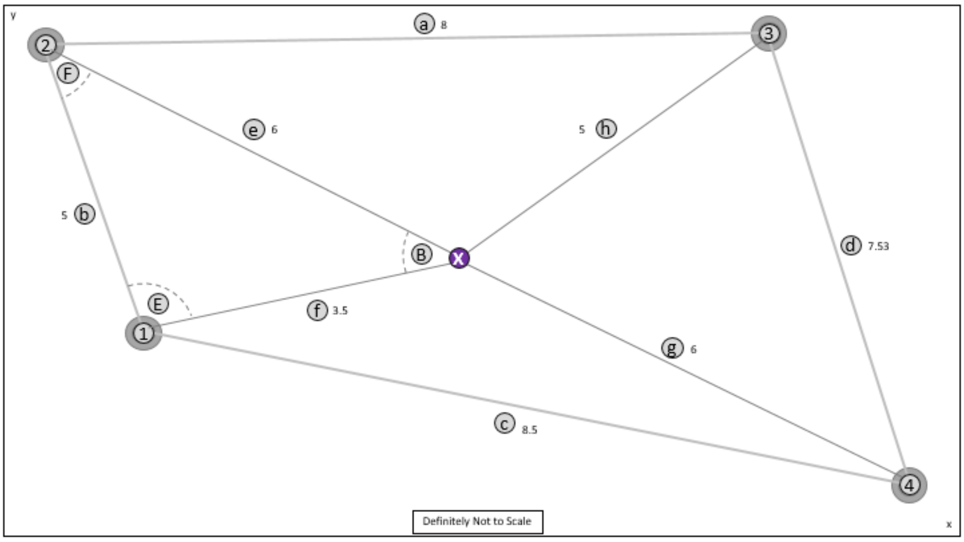
See **Appendix 3 – Calculating Extruder Coordinates** for full worked solution

2.6.4 Irregular Quadrilateral Print Envelope



Annotated Top View of Irregular SALEM Print Envelope: Image 1

The Leg Structures are located manually, so there is a high potential for human error resulting in a print envelope that is not a perfect right-angle quadrilateral. The print software must therefore be capable of mapping a relative grid within the print envelope that lets it know where each Hoist is in relative terms. For our example we are assuming that the distance between each Hoist has been measured by sensors on the Hoist Housing and are absolute giving us the length of the sides of the polygon. The interior angles of a four-sided polygon always equal 360 Degrees. If we want to know the shape of the print envelope, we need to determine the specific angles of each corner.



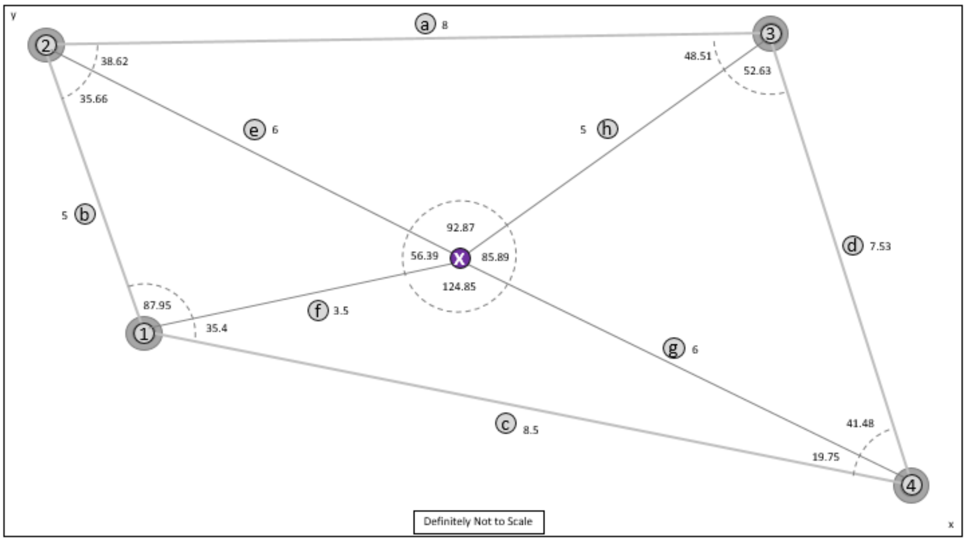
Annotated Top View of Irregular SALEM Print Envelope: Image 2

In the above example we have specified a location for the Extruder within the print envelope. At this point we have inputs from the Hoists on Cable extension lengths, found using measurements of extension lengths at a random point in the print envelope. From a birds-eye view, it forms four triangles and for each triangle we have 3 known sides meaning we can use the Law of Cosines to determine the interior angles:

$$c^2 = a^2 + b^2 - 2ab\cos(C)$$

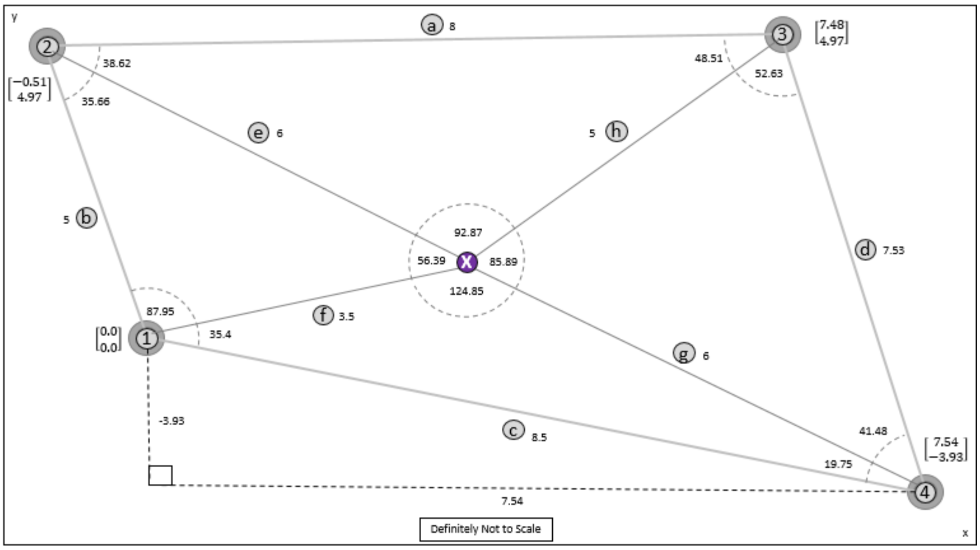
If we rearrange this formula to solve for angle (*C*) we get:

$$C = cos^{-1}\left(\frac{(a^2 + b^2) - c^2}{2ab}\right)$$



Annotated Top View of Irregular SALEM Print Envelope: Image 3

After repeating this process for all angles, we can add up the interior angles and find the total is 360 Degrees. The Extruder intersect angles also add up to 360 confirming that we have calculated the interior angles of the quadrilateral correctly. We now know the size and shape of the polygon. From here we can determine cable length parameters from Cartesian coordinates by solving right-angle triangles from vector $\begin{bmatrix}0\\0\end{bmatrix}$ to the other 3 Hoists, much in the same fashion described in the Right-Angle print envelope example.

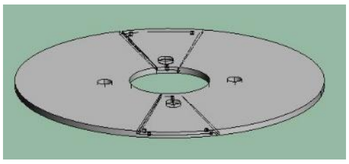
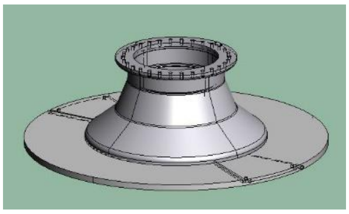
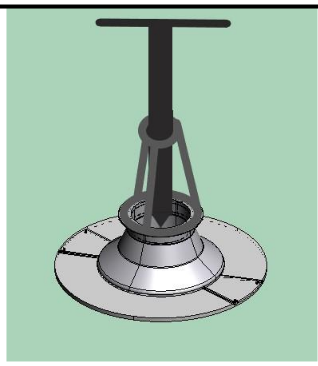
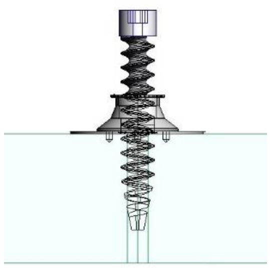


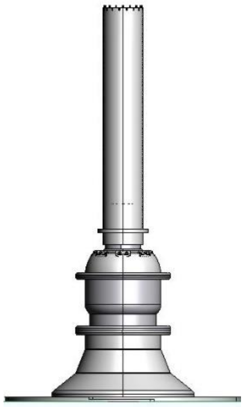
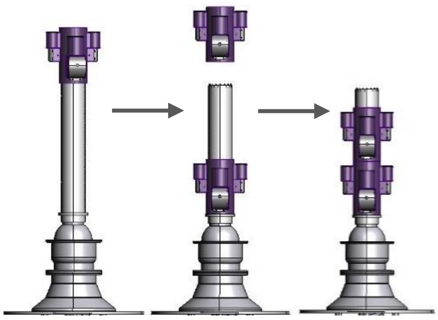
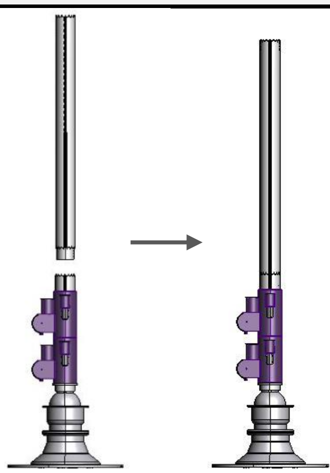
Annotated Top View of Irregular SALEM Print Envelope: Image 4

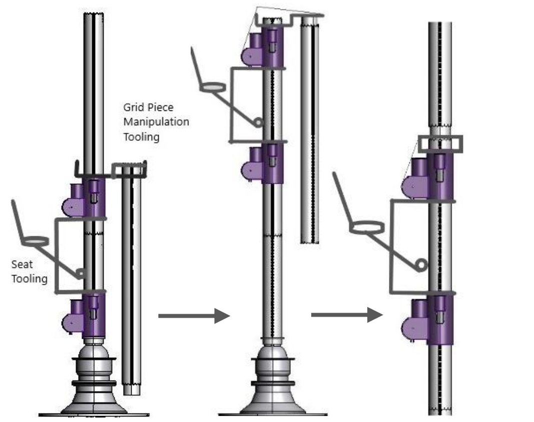
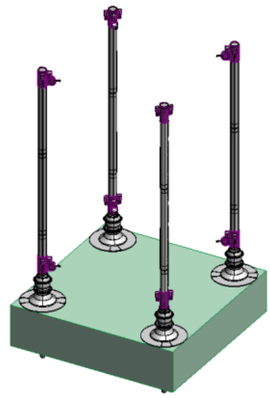
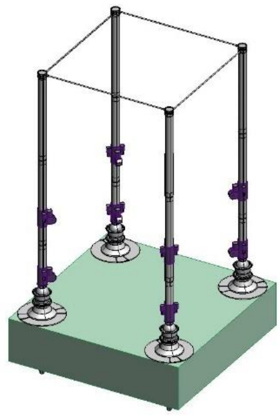
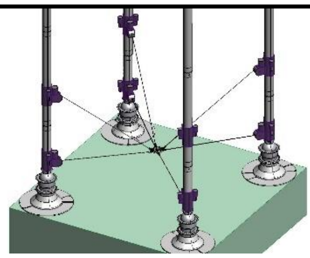
For a full worked solution please refer to **Appendix 3 – Calculating Extruder Coordinates**

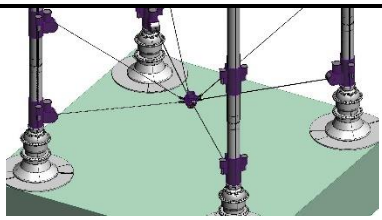
2.7.0 Two-Person SALEM Printer Assembly Sequence

One of the key success factors for the SALEM Printer is that it is possible to erect without the use of any overhead cranage and with minimal crew. The reason for this is that the printer is intended to print in remote, hard to access locations such as Antarctica and Mars. Any requirement for overhead cranage will greatly increase the burden of package delivery and, for Mars in particular, will significantly raise the risk of a mission-ending complication arising. By ensuring that all components can be manually handled it allows greater flexibility in the assembly and makes it easier to deal with unforeseen or less than ideal circumstances. The Assembly and Set-up method for the SALEM printer is envisioned as the following:

Step No	Step detail	
1	**Level and prime print zone ready to receive printer including Foot locations:** Clear the print area of any shrubbery or rocks and even out the ground as much as possible.	
2	**Measure out the foot piece locations:** This does not need to be 100% accurate as the print envelope is relative and calibrated before printing begins. The foot piece locations could in theory be entirely random without affecting the print quality.	
3	**Assemble Distribution Plates and Foot Bottom Housings at location:** This should be achievable with a 2-man lift by ensuring that every individual component of the foot piece (i.e. Ground screw, Distribution Plates, Foot Sole, Pivot Joint) is less than 44KG and assembling the Structure Feet up at location. The current design enforces assembly at location due to the Ground Screw being housed inside the Foot assembly.	 
4	**Drill a witness hole for each Foot location:** To do this activity the Foot piece should be adapted with tooling and double up as a Drill. In this way the tooling for this activity can be reduced to the Drill piece and some motorised/ hand operated tooling to turn the drill piece.	
5	**Secure ground screws into place:** This should be done using the same/similar tooling used to create the witness holes.	

6	**Fit Pivot Joint Assembly:** Again, this should be a 2-Man Manual handling activity. The pivot Joint assembly can be disassembled to reduce lift weight.	
7	**Fit initial Grid Piece to Foot Assembly:** The initial Grid Piece interfaces with the Pivot Joint and should be light enough for a 2-Man manual lift. Timing slots in the shaft of the Pivot Joint and the initial grid piece prevent the structure from moving radially.	
8	**Calibrate and Lock Feet to sit vertical:** This is the most important calibration of the assembly. If the Structure Legs do not sit perfectly vertical the print could experience tolerance drift at different heights. Calibration is achieved by adjusting the Pivot Joint and then securing the Locking Plates. Ideally this would be done automatically.	
9	**Fit Variable Hoists to assembly:** Hoists should be below 2-Man Manual handling limit and are fitted by sliding over the top of the Initial Grid Piece. During this process the Hoist should be electrically connected to the control unit and a few basic operability procedures should be performed to ensure Hoists are in full working order. This includes calibrating the Hoist cable length by retracting the cables fully and setting as zero.	
10	**Calibrate Hoist Separation:** Hoists are dropped to the lowest position such that both Hoists per leg are married up to each other on the bottom stop. This is then set as the Minimum Separation coordinates.	
11	**Fit first variable Grid Piece:** The first Grid Piece after the Initial Piece should be manually offered up and fitted. Grid Pieces are designed to slot into one another and are fixed in place with three sunken bolts. Timing slots ensure that the Grid Pieces align correctly to keep a continuous track for the Hoists to traverse along. The Foot assembly, Initial Grid Piece and first Grid Piece bring the assembly to a height of approx. 3.5 meters.	

<table>
<tr><td>12</td><td>Add remaining Grid Pieces to assembly: Tooling can be designed to actuate off the Variable Hoists to lift and locate the Grid Pieces and, given the correct torque capabilities, can be used to platform off of and act as a lift for persons to complete the necessary fitting work on each Piece at height without a supporting overhead crane. The Hoist cable is used to manipulate the Grid Piece into place. Number of Grid Pieces required is dependent on the required height of the printer.</td><td>
</td></tr>
<tr><td>13</td><td colspan="2">Fit Grid Tops to Leg Structure: These Top Pieces prevent the Hoists from accidentally travelling too high and falling off. This can be fitted using the same seat tooling described in step 12.</td></tr>
<tr><td>14</td><td colspan="2">Repeat Steps 3 to 13 for the other 3 Leg Structures</td></tr>
<tr><td>15</td><td>Calibrate Max Hoist height: The top 4 Hoists are manually travelled to the Top of the Leg Structures and the bottom Hoists are bottomed out. The Hoists then use sensors to measure the relative location of and determine max travel for each Hoist based on the locations of the other 7 Hoists.</td><td></td></tr>
<tr><td>16</td><td>Fit Support links to Structure: These link the legs together at variable heights providing further support to the Structure. To fit them, tooling platforms can be fitted to the Hoists to lift the links and persons to required height. Support links are first fitted to the top of the assembly and progressively added below in necessary intervals to maintain Structure Integrity.</td><td></td></tr>
<tr><td>17</td><td>Fit Extruder Cradle to assembly: Manually extend all Hoist cables and link each cable to the Extruder Cradle. Cables are then manually retracted until the cradle is tightly and evenly suspended.</td><td></td></tr>
</table>

18	**Fit Extruder to Cradle:** The Extruder is lifted and located into the Cradle and secured with bolts. For a 2-Man lift it may be necessary to split the Extruder assembly into components and build it up on site.	
19	**Calibrate the Print Envelope:** Manually travel the Extruder to each corner of the intended print envelope and then retract each Hoist cable until the Extruder is suspended tightly at the location and each Hoist maintains a predefined torque. A reference point is saved at each corner. This allows the printer to calculate the necessary cable extension length for positioning the Extruder anywhere within the print envelope. Multiple reference points can be taken within the print envelope for further validation, however only one is necessary to calibrate the printer.	
20	**Assemble and Locate the Cement Tank:** This sits just outside of the print envelope. No individual component of the cement tank should be above 44kg and the tank will be assembled (dry) at location.	
21	**Electrically Connect and check the Extruder:** a few basic operability procedures are performed to ensure the Extruder is fully operable and all calibration points were successful.	
22	**Perform operability Checks on assembly:** Several manoeuvres are performed with the assembly to ensure the printer operates as intended.	
23	**Connect the Cement Hose to the Cement Tank and Extruder:** Cement Hose is looped over the top of the support structure to ensure the hose does not snag on any of the cables when moving.	
24	**Final Operability Testing on printer:** To ensure the printer moves correctly when fixed to the Cement Tank and the Extruder operates correctly in use.	
25	**Scan Print Area:** A 3D scan of the ground is performed with the Extruder Nozzle to generate a digital representation of the floor.	
26	**Print foundation:** Using data from the floor scan, an even foundation is printed.	

2.8.0 Design Summary

2.8.1 Design Risks

The design Risk register forms the basis of experimental requirements by identifying the potential modes of failure during operation and service. A design risk register has been created as part of this proposal that provides a first pass at defining what experiments and tests might need to occur to certify SALEM for commercial use. Below are the top 10 design risks so far considered:

Top 10 Design Risks					
No	Name	If… then…	P	I	Score
1	Cement freezes during operation	If the cement system is not heated, then cement may freeze and stop operation or potentially damage the printer.	5	4	20
2	Hoist Cable length is miscalculated due to angled operation	If the Hoist cable is extended at an angle, then there is potential for miscalculation which will affect the print quality.	4	3	12
3	Extruder nozzle extrudes wrong profile	If the extruder Nozzle design is not improved or altered, then the extrusion profile will be inaccurate and distorted.	4	3	12
4	Ground Screw too heavy	If the weight of the ground screw cannot be reduced, then it will not be possible to assemble the printer with just 2 people without the use of a crane.	3	4	12
5	Person falls during printer assembly	If the 2-person assembly tooling is not designed well, then there may be a risk of life during assembly.	2	5	10
6	Pivot Joint drifts post assembly	If the Support Structure Pivot Ball locking feature is not sufficiently secure, then the support structure could become out of calibration during print.	3	3	9
7	Deflection causes misalignment	If the Hoists are overstrained whilst in operation, then the support structure could deflect inward causing a misalignment and potentially distorting the print.	3	3	9
8	Cement Hose deteriorates	If the Cement Hose material is not robust, then Solar radiation may cause deterioration/failure in locations such as Mars.	3	3	9
9	Extruder pump screw Jams	If grit and other FOD over-encumber the Pump Screw, then it may fail.	3	3	9
10	Cement Pump not powerful enough	If the Cement System Screw Pump cannot achieve a high enough power rate, then cement may not be fed to the Extruder correctly	2	3	6

For the full detail of design risks, see **Appendix 12 – Design Risk Register**

2.8.2 Weight

The overall weight of the SALEM Printer can be found by adding all the constituent modules of the printer together. For a SALEM Printer capable of printing in off-grid locations such as Mars, we find the total weight to be:

Concept Total Package (5x5x5m) Weight Assessment				
Part Name	**QTY**	**Estimate Type**	**Mass (Kg)**	**Total Mass (Kg)**
Support Structure	1	Calculated	1,553	1,553
Hoist Assembly	8	Calculated	38.9	311.2
Extruder (Dry)	1	Calculated	56.4	56.4
Cement Delivery System (Dry)	1	Calculated	129.8	129.8
Power & Control System	1	Calculated	725	725
Tooling	1	Allowance	250	250
Total SALEM Printer Package Weight				**3,025.4 Kg**

This assessment includes a Solar Array and Battery Pack plus the weight of the tooling required to erect the printer. For applications on Earth in areas with access to the power grid it will be unnecessary to power the system using a Solar Array, so we can therefore omit the weight for these items reducing the package weight down to approximately 2,325 Kgs.

The Support Structure constitutes the bulk of the weight of the printer and the current design has been conceptualised as a bulky, heavyweight structure to reduce the possibility of deflection during print. It is likely that this support is far above actual requirements and will see reductions to weight in later design iterations. The Support Structure also currently features four Ground Screws each weighing approximately 125 Kg. These screws act as anchors to the ground to prevent the Printer from moving during print. It may prove unnecessary to have such features in place for the final design due to the weight of the Structure itself. If this element could be designed out of the SALEM Printer, we could reduce the package weight further, down to approx. 1,800 Kgs making this Printer one of the lightest C3DP concepts available.

2.8.3 Benefits matrix

Now that we have defined what the SALEM Printer is and how it will operate, we can compare it to other C3DP printing methods using the benefits matrix defined in section 1.1.2.

Factor	Rotary Arm	Overhead Crane	Modular	Robotic	SALEM
Package Weight	4	2	1	4	3
Print Speed	4	4	3	1	4
Scalability	2	2	4	2	5
Print Quality	3	4	4	2	4
Efficiency	4	3	2	2	4
Set-up Time	4	1	5	4	2
logistics	3	1	1	2	4
Total	**24**	**17**	**20**	**17**	**26**

The current package weight of the SALEM Printer outperforms overhead crane style printers as the Support Structure needed for the Extruder is drastically reduced using Hoist cables instead of solid grids for movement. Currently, Rotary Arm Printers and Robotic Printers have a marginal edge over SALEM in terms of package weight, however this may change as the SALEM concept develops and is optimised.

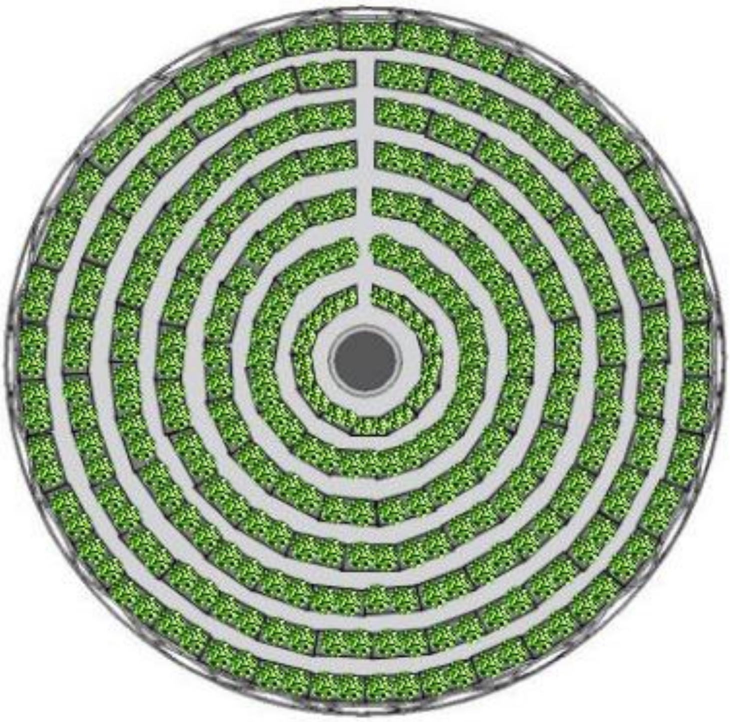
Once fully developed the SALEM Printer is expected to achieve rapid (up to 1.6m/s) travel speeds with millimetre accuracy for minimal energy costs by drastically reducing the mass of the Extruder travel system with the use of cables for suspension. Logistics for SALEM is also expected to be comparatively easy since the Printer can be collapsed small enough to fit into standard transit vehicles and requires no overhead cranage to assemble, meaning it can be deployed virtually anywhere on planet and could even potentially be used for off-world applications.

In terms of scalability, the SALEM Printer is the only C3DP concept that could theoretically produce high-rise buildings on-site without the need for any additional parts or segments to be manufactured off-site. For all these reasons the SALEM Printer scores above all other C3DP types overall in this assessment. Setup time for the SALEM printer is a limiting factor as it is currently expected to take approximately one week to assemble. This will improve if it is possible to redesign the Support Structure without Ground Screws to lock it into position.

3.1.0 Application Analysis - Vertical Farming

In this chapter we will analyse the benefits, cost and profitability of a 20-Acre Vertical Farm constructed using the SALEM Printer. For this analysis we will assume that the Vertical Facility is cylindrical, has a diameter of 30m, 30 floors for crop farming and each floor has a minimum of 0.67-Acre farm capacity. To ensure that the facility can be constructed to as high as 30 floors a thin steel support frame (Approx. 10t per floor) will be integrated into the building design giving greater tensile strength to the final structure.

Vertical Farming is the practice of producing crops, medicine and other natural products in a 3 dimensional 'stacked' manner. Simply stacking potted plants on shelves can be considered Vertical Farming and limited scale such as this are the typical modern applications for this type of farming.



Example 20-Acre Vertical Farm floor layout

Side View of Example 20-Acre Vertical Farm

The general concept of Vertical Farming is not new, having been first introduced in 1915 by Gilbert Ellis Bailey in his book *Vertical Farming,* and despite boasting a plethora of benefits to traditional farming, industrial vertical farming is still exceptionally rare due to the prohibitively high set-up costs involved. Most significant scale Vertical Farms in use today are either integrated into the design of other projects (such as skyscrapers) or are the result of repurposing warehouses and shipping containers. With the SALEM Printer, the cost of constructing a purpose built, industrial scale Vertical Farm is brought into a realistic range by drastically reducing the cost and time to construct the Farm shell structure.

3.1.1 Drawbacks to Vertical Farming

The main drawback to Vertical Farming is the initial cost of constructing the farm which has historically been prohibitively high. Unlike traditional farming there is also an overhead cost of electricity for UV lighting, air conditioning and other climate control systems, however this is offset by generally much higher crop yields.

3.1.2 Benefits of Vertical Farming

Vertical Farming has many innate benefits over traditional farming methods, largely thanks to Vertical Farms being almost entirely divorced from the whims of nature. That is to say that, unlike traditional farming, Vertical Farms are capable of being entirely controlled, from light intensity and duration, to atmospheric pressure and content. With the utilisation of hydroponics, it's also possible to produce a much higher yield than traditional methods whilst also reducing or even removing the impact of pesticides and insecticides on the natural world. The greatest benefit of Vertical Farming however, comes from the simple fact that much more food can be produced per foot of land. Traditional Farming is 2 dimensional in nature and as such, requires monumental swathes of land to sustain the human population. In fact, fao.org estimates that we use approx. 36 percent (1.5 billion ha) of all arable land on earth to feed the current human population. By adding a 3rd dimension to the equation we could realistically reduce our agricultural footprint by more than 98% whilst simultaneously drastically reducing the risk of crop loss due to drought, disease and natural disaster.

Vertical Farm benefits		
No	**Benefit**	**Explanation**
1	Reduced physical footprint	Vertical Farming allows a far greater yield of produce per foot of land by stacking crops on top of one another.
2	Control of light intake	Vertical Farms use UV bulbs to provide the light required for photosynthesis and do not rely on natural sunlight. This means the number of 'daylight' hours and the intensity of that light can be fully controlled.
3	Air quality	By utilising air conditioning and particulate filters, the air quality of Vertical Farming can be maintained at a much higher standard than traditional methods, reducing incidents of crop disease.
4	Reduced impact of disease	As Vertical Farms are modular in nature, if disease should breakout on one floor it is unlikely to affect other floors. This means only a small portion of crops will be destroyed in any single disease outbreak. Hydroponics also remove soil from the process further reducing the likelihood of disease.
5	Temperature control	Indoor farming also means that temperature can be controlled, and each floor can be individually optimised to provide the correct climate for the crop of that floor.
6	Moisture control	Instead of having to rely on rain for moisture, water intake can be controlled to ensure crops are never over or under hydrated. Hydroponics provide an opportunity for even greater moisture control.
7	Air content control	Most crops can thrive with a higher CO2 content than what is present on earth today. With Vertical Farming, additional CO2 can be fed into the grow environment to produce greater yields.

8	Reduced impact of pesticides to the environment	Many Insect and vertebrate species have been detrimentally impacted by the advent and use of insecticide and pesticides including critical losses of Bee species and other key pollinators. By utilising Vertical Farms these harmful chemicals are removed from natural environments reducing harm to nature.
9	Reduced requirement for Pesticides	Due to the clinical nature of Vertical Farming providing a cleaner environment for crops, the need for insecticides and pesticides is greatly diminished meaning healthier produce can be grown.
10	Fewer boundaries to Farm location	As Vertical Farming is usually indoors and climate controlled, they can effectively be erected and utilised anywhere on the planet meaning food can be farmed in places currently impossible such as Antarctica, the Sahara and even Mars.
11	Reduces Crop loss from theft and damage	Traditional Farms expect a level of crop loss due to theft from animals and humans as well as from crops being trampled. Only staff have access to the crops in Vertical Farms eliminating this issue.
12	Protection from natural disasters	Farming indoors provides added protection against unforeseen disasters such as flooding, wildfires, hurricanes and other disasters that would typically devastate a crop.
13	All year-round crop growth	By controlling all aspects of the growing environment there is no seasonal drive on crop growth. Crops can be grown all year round with almost the same cost and effort.
14	Less water required	Hydroponic farms are closed systems and as such, a large portion of the water used can be recycled. Hydroponic crops generally require just 10-15% of the water intake of traditional farms.
15	Higher crop yields	For all the reasons stated above, Vertical Farming can and will provide much higher crop yields than traditional methods with fewer incidental losses.

3.1.3 Estimated Build Cost of a 20-Acre Vertical Farm

Below is a projection of the cost to construct a 20-Acre Vertical Farm. The projection is for materials and construction labour resources only and does not include the cost of acquiring land or any potential taxes or surcharges as these will significantly vary from location to location. The projection assumes that all off-the-shelf items will be charged at commercial rates and no bulk discounts will be applied. This cost analysis should therefore be considered as a rough gauge of required investment only and not a definitive cost breakdown.

Vertical Farm (20 Acre) Building Cost					
Products	Quantity	Cost $ (single)	Cost Units	Cost $ (Total)	Estimate Type
Cement	275	60	$/Ton	16,500	CAD & Calculation
Sand	1,375	30	$/Ton	41,250	CAD & Calculation
Steel	300	620	$/Ton	186,000	Calculation
Solar Tiles	111,831	21.85	$/ft^2	2,443,507	Calculation
Electrical fixtures	32	5,000	$/Floor	160,000	Allowance
Tesla Batteries (Powerwall)	40	7,740	$/13.5 KWh	309,600	Calculation
Hydroponic Tanks	190,851	5.06	$/ft^2	965,706	Calculation
LED Full Spectrum Grow Light	12681	30	$/Unit	380,430	Calculation
Water Pumps and Tanks	30	6,000	$/Floor	180,000	Allowance
Electronic Appliances	30	10,000	$/Floor	300,000	Allowance
3.5kwh Air Conditioning System	30	20,000	$/Floor	600,000	Reference
Tile Flooring	190,851	5	$/ft^2	954,255	Reference
Interior Finishing	30	8,000	$/Floor	240,000	Allowance
Furniture	30	10,000	$/Floor	300,000	Allowance
Packaging Equipment	1	150,000	$/ machine	150,000	Allowance
Resources					
Plumbing Labour	190,851	4.5	$/ft^2	858,830	Calculation
Steel Support Manufacture	30	40,000	$/Floor	1,200,000	Allowance
Structure Construction	22,560	17	$/hr	383,520	Calculation
Electrical Labour	190,851	3.5	$/ft^2	667,979	Calculation
Total				**$10,337,576**	

For calculation assumptions see ***Appendix 5 – Vertical Farm Costing***

3.1.4 Estimated 20-Acre Vertical Farm Yield PA

Below is an example of potential yields from a 20-Acre Vertical Farming facility. Expected yield figures have been taken from nevegetable.org [9] and represent low-medium yields of traditional farming methods. These figures should be considered conservative given that hydroponic farming will typically significantly increase crop yields for many species with some (such as tomato plants) seeing as much as a 100-fold increase in productivity. Add to this, the many benefits outlined in the table above such as the capability for year-round growing, it is conceivable that actual yields of a real life 20-Acre Vertical Farm would be orders of magnitude higher than stated here. Vegetable prices have been taken from UVM.Edu [10]

Floor	Produce/Function	$/lbs (retail)	lbs/ Acre	Lbs/Floor	$/Floor
1	Storage & Packaging	N/A			
2	Water & Electricity Processing	N/A			
3	Lettuce	2.5	40,000	26,800	67,000
4	Lettuce	2.5	40,000	26,800	67,000
5	Lettuce	2.5	40,000	26,800	67,000
6	Potatoes (coloured)	2	25,000	16,750	33,500
7	Potatoes (Fingerling)	3	15,000	10,050	30,150
8	Potatoes (Fingerling)	3	15,000	10,050	30,150
9	Carrots	2	26,000	17,420	34,840
10	Carrots	2	26,000	17,420	34,840
11	Cauliflower	2.5	14,000	9,380	23,450
12	Cucumber	2	20,000	13,400	26,800
13	Dry Bulb Onions	2	40,000	26,800	53,600
14	Dry Bulb Onions	2	40,000	26,800	53,600
15	Parsnip	2.5	20,000	13,400	33,500
16	Peas	4	9,000	6,030	24,120
17	(green) Bell Pepper	2	30,000	20,100	40,200
18	(Red) Bell Pepper	2	30,000	20,100	40,200
19	Leeks	3	32,000	21,440	64,320
20	Spinach	5	12,000	8,040	40,200
21	Spinach	5	12,000	8,040	40,200
22	Squash	2	30,000	20,100	40,200
23	Squash	2	30,000	20,100	40,200
24	Strawberry	20	10,000	6,700	134,000
25	Strawberry	20	10,000	6,700	134,000
26	Strawberry	20	10,000	6,700	134,000
27	Tomato	2.5	30,000	20,100	50,250
28	Tomato	2.5	30,000	20,100	50,250
29	Tomato	2.5	30,000	20,100	50,250
30	Turnip	1.5	24,000	16,080	24,120
31	Turnip	1.5	24,000	16,080	24,120
32	Beans	4	8,000	5,360	21,440
Total				435,500lbs	$1,461,940

3.1.5 20-Acre Vertical Farm Overhead Cost Analysis

In order to effectively run a Vertical Farm, there are several overheads to fulfil. The type of operational overheads to consider range from consumables such as electrical power to run the grow Lights, Air conditioning and other control systems, and plant nutrients, to labour resources to maintain and nurture the crops. In terms of labour, we can assume that it will be necessary to have a number of permanent staff such as ‘farm technicians’ that will monitor the crops as well as perform the manual cultivation activities that are unlikely to be automated, at least at first. These include preparation, planting, harvesting, spot checking and manual intervention if a problem should arise. For the purpose of this analysis we will assume that all day to day maintenance such as watering and climate control will be fully automated and not need excessive intervention from humans to maintain.

In traditional farming, the amount of labour required is highly dependent on what is being grown and what farming tools are available, but a single farmer is generally able to maintain 1 acre of land with only additional seasonal assistance for harvesting if no heavy machinery (such as tractors) are used. With heavy machinery, a single farmer may be able to manage up to 40 acres of land solo. With traditional farming there is however a much greater potential for issues to arise that require intervention such as weeds and pests. For our analysis we should assume that these issues will be largely redundant thanks to hydroponic farming techniques and a single farm technician will be able to manage the equivalent of 5 acres of land. Vertical Farming also enables staggering of harvest times to remove the necessity of hiring seasonal workers for this activity further optimising labour overheads. Other more marginal labour overheads include inventory and logistical control, management, maintenance engineering and cultivational expertise.

For analysis of consumables and maintenance overheads we also need to make some broad assumptions. grow lighting provides diminishing light outputs as bulbs age so we should assume that roughly 10% of all bulbs should be replaced per year to maintain optimal light outputs. There will also be maintenance costs associated with the hydroponics systems as well as packaging and water consumption costs which need to be factored.

Vertical Farm Overheads					
Products	**Quantity**	**Cost $ (single)**	**Cost Units**	**Cost $ (Total)**	**Estimate Type**
Consumables					
Electricity	2,837,180	0.1	$/KWh	283,718	Calculation
Lightbulbs	1,263	30	$/Bulb	37,890	Calculation
Hydroponics parts	9,543	5.06	$/ft^2	48,288	Calculation
Water Filters	120	12	$/Filter	1,440	Calculation
Plant Feed	20	81	$/acre	1,620	Reference
Water	4,252	1.5	$/1000 Gal	6,378	Calculation
Consumables	1	10,000	Total	10,000	Allowance
Packaging	435,000	0.15	$/lb	65,250	Allowance

Labour					
Farm Technician	8,320	17	$/hr	141,440	Calculation
Engineering/ Maintenance	104	30	$/hr	3,120	Calculation
Management	522	40	$/hr	20,880	Calculation
Logistics & Packaging	2,088	15	$/hr	31,320	Calculation
Cultivation Expertise	104	50	$/hr	5,200	Calculation
Total				$651,343	

For calculation assumptions see ***Appendix 4 – Farm Energy Consumption & Production***

3.1.6 20-Acre Vertical Farm Investment Return Analysis

In the previous sections of this chapter we have defined the construction costs, overhead costs and productivity of an example 20-Acre Vertical Farming facility. With this information we can draw some conclusions on the potential profitability of such a facility. By subtracting the total overhead cost from the revenue created by produce sales, we can conclude that:

$$Gross\ Yearly\ Profit = Revenue - Overhead\ Costs$$
$$Gross\ Yearly\ Profit = \$1{,}461{,}940 - \$651{,}343 = \$810{,}597$$
$$Profit\ Margin = \frac{Gross\ Profit}{Revenue}$$
$$Profit\ Margin = \frac{\$810{,}597}{\$1{,}461{,}940} = 0.5545 = 55.5\%$$

With a projected profit margin of over 55%, provided the assumptions these calculations are based on are at least loosely accurate, we can expect a Vertical Farm of similar specifications to this analysis to be extremely profitable. It should be noted though, that this figure represents the profit margin that can be expected once the initial investment to construct the farm has been repaid. To determine how long it will take for the farm to fully return the investment for construction, assuming all profit is used to repay the sum, we can use:

$$Investment\ Return\ Time = \frac{Investment}{Gross\ Profit}$$
$$Investment\ Return\ Time = \frac{\$10{,}337{,}576}{\$810{,}597} = 12.75\ Years$$

If each facility is intended to be in commission for at least 30 years then an investment return time of just under 13 years is modest, but reasonable. Nonetheless we can improve on this return time by optimising production; For example, we can see from our table of yields that certain crops are far more profitable than others. If the farm was initially configured to exclusively farm strawberries for instance, we could expect a revenue of approx. $4m, with broadly the same overhead costs. This would reduce the investment return time to around 3 Years. The 20-Acre farm assumes that only one layer of produce is produced on each floor, but many crops can be stacked in multiple layers. Lettuce for instance, could be grown comfortably in stacks six plants high on each floor meaning a six-fold increase to crop production. It is also important to again stress that the production yields used for these calculations are that of a low-medium yielding traditional farm and Vertical Hydroponic Farming has consistently been shown to produce far higher yields than a typical farm can, consequently an investment return time of 13 years should be considered worst case scenario.

For calculation assumptions see ***Appendix 5 – Vertical Farm Costing***

3.1.7 Construction Time using SALEM

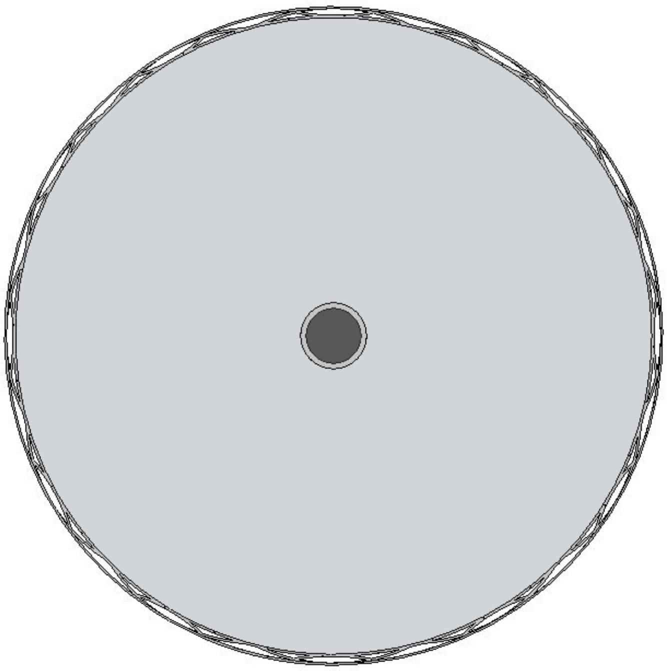
The SALEM Printer will drastically reduce the time it takes to construct large scale structures such as high-rise buildings fundamentally by reducing the amount of delta movement required to assemble material into structures. The speed at which we can extrude structures will depend on the travel speed of the Extruder and the Cement flow rate.

The total print time for the Vertical Farm would be the sum of the individual elements of the print. The printer will first need to be setup and calibrated, then a foundation layer must be printed to provide a platform for printing the final structure on. There is then a succession of floors to be printed. Each level will require a certain amount of printing down time to allow the construction crew to lay lintel beams and other supports which can also be printed by SALEM Printers.

Activity	Quantity
Clear print space	1
Setup SALEM Printer	1
Print Foundation	1
Print Walls	32
Print Floor	32
Disassemble SALEM Printer	1

3.1.7 Structure Walls

If we assume that an average Extruder Travel speed of 1.6m/s can be achieved, we can calculate print time for our case of a Vertical Farm by making assumptions on the thickness of the walls and the extrusion thickness. For our assessment we will assume that the average thickness of the exterior walls will be 0.3m and the Extruder will on average extrude material 0.03m wide and 0.03m thick. The Vertical Farm has a diameter of 30 meters and is 32 floors tall making a total height of 96m.



Example 20-Acre Vertical Farm Floor Structure

To approximate the time to print the walls of one 3m tall farm floor we can multiply the circumference of the structure by the number of rotations required to print a single layer and by the number of layers required for the full floor and then divide it by travel speed. We can express this as the formula:

$$T = \frac{2\pi r \times \mathrm{W} \times \mathrm{L}}{S}$$

Where:

- T = Print Time
- W = No of extrusions per layer
- L = No of extrusions per floor
- S = Extrusion Speed (m/s)

$$T = \frac{2\pi r \times 10 \times 100}{1.6m/s} = 58{,}905\ Seconds$$

If we convert this figure into hours, we find that to print a single Vertical Farm Floor it will take 16.36 Hours. This does not include the time for any interior walls. The concept Vertical Farm has an elevator shaft running through the centre of the facility. Assuming this has a diameter of 3m we will add a further 1.64 hours to the print time for a single floor bringing the total time up to 18 Hours.

3.1.7 Foundation & Floor Layers

If we assume that the floor and foundation layers will be 0.3m thick we can calculate the approximate print time of these print elements too. For the structure walls we assumed that all 10 extrusions to complete a layer would have the same diameter. In reality; they will all have slightly different diameters, getting smaller the more interior the extrusion is. For foundations and floors, we can break a single layer into hundreds of consecutive rings. By adding up the circumference of all the rings we find the total travel distance for one layer.

In Appendix 5 tab 'Foundation Layer' we calculate that to print a single 0.03m thick layer for the floor or foundation of our Vertical Farm, the Extruder would need to travel a total distance of 23,609m. To print a floor 0.3m thick, we times the travel distance for a layer by the number of total layers. Print time can then be determined by dividing by travel speed as we did for the structure walls:

$$T = \frac{23{,}609 \times 10}{1.6} = 147{,}556\ Seconds$$

If we convert this to hours, we find the total time to print a floor for our Vertical Farm is 41 hours. The foundation layer will likely extrude at a slower rate than a regular floor as the printer will need to map the floor out and control the flow rate with more finesse. If we assume this layer will be done at 0.5m/s we find the foundation layer would take 131.2 Hours to complete. This does not include the savings in time we could achieve by varying the Extruder Nozzle diameter which would drastically reduce the time it takes to print floor and foundations.

3.1.7 Total Print Time

Now we know how long it takes to print the constituent parts of the Vertical Farm we can tally up the total time it could take.

Activity	Quantity	Time (Hours)	Time Total
Clear print space	1	72	72
Setup SALEM Printer	1	168	168
Print Foundation	1	131.2	131.2
Print Walls	32	18	576
Print Floors	32	41	1312
Disassemble SALEM Printer	1	72	72
Total			**2,331.2 Hours**

If the SALEM Printer was in continuous operation without pause, it would be possible to print a full 20-Acre Vertical Farm in as little as 100 days. This doesn't take account of down time during build however; there would be multiple points during an actual print to fit accessories, check print quality or fit lintels and other supports. If we assume this will add an additional 36 hours per floor, we can expect a print to take approx. 145 Days to complete at optimal performance. If we expect at least 20% delay from unforeseen circumstances, then a real-world construction time of approx. 6 months should be a reasonable expectation.

3.1.8 Sustaining Humanity with Vertical Farming

With the human population expected to exceed 8 Billion individuals by 2024, over a third of global arable land already landscaped for agriculture and a climate that is rapidly declining toward inhospitality, it is clear that to continue to survive as a species on Earth, a step change towards sustainable living is needed. Many bold and innovative steps have been taken across the globe to tackle some of the existential issues that we are facing now and that will be exacerbated as the climate declines. The advent of Solar and Wind power will ween us from a century old dependency and Electric Vehicles may be the final push needed to kick the fossil habit once and for all.

Even the stars, that were once only for signs, may one day become home thanks to the leaps made in reusable rocket technology in the last few decades, but for all the advances we have made since the industrial revolution, one field has stayed stubbornly unchanged; Agriculture. Yet agriculture has always been, and continues to be, humanities largest physical footprint on the planet. We have expanded endlessly into the great expanse. Technology has brought us closer together. The world has gotten smaller. But our footprint has only grown.

Vertical Farming offers a chance, for the first time, to really impact the size of our physical footprint, allowing more room for the countless others we share our home with. The previous sections of this chapter have shown that it isn't only feasible and practical to produce food through Vertical Farming with the use of the SALEM printing concept, but also potentially lucratively profitable. This section will attempt to look at the feasibility of feeding the entire human population using only Vertical Farming.

For the purpose of this analysis we will assume that the human population will hit and then remain static at 8 billion individuals, that everyone requires on average 2000lbs of food per year to sustain themselves and that the SALEM printer will be sufficiently developed by 2024 to begin producing Vertical Farms in earnest. We will also assume that all Vertical Farms will be built to the same 20-Acre specification used for the analysis in previous sections of this chapter and the conclusions made on cost and profitability will hold true.

With these assumptions we can find the average number of people that can be sustained by each vertical farm with the following equation:

$$No\ People\ per\ Farm = \frac{Farm\ Production\ Rate}{Consumption\ Rate\ per\ person}$$

$$No\ People\ per\ Farm = \frac{435{,}500}{2000} = 217.75$$

Using this figure, we can then determine the total number of farms required to feed the total human population:

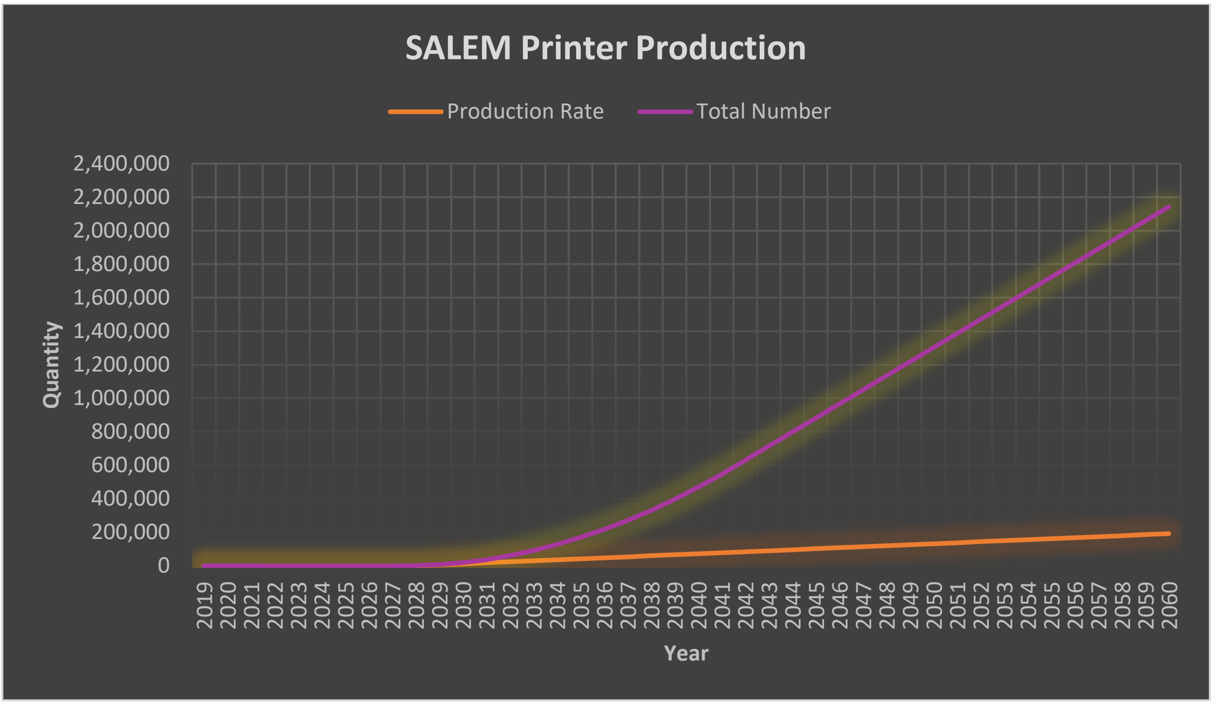
$$Total\ Req'd\ Farms = \frac{Total\ Population}{No\ People\ per\ Farm}$$

$$Total\ Req'd\ Farms = \frac{8{,}000{,}000{,}000}{217.75} = 36{,}739{,}380$$

So, to cover the entire human populations direct food requirements we would need just short of 37 Million 20-Acre facilities. For reference, Manhattan contains approximately 60,000 high-rise buildings so we will need to construct the equivalent of Manhattan over 600 times to achieve the production capabilities to feed the entire planet. At first glance this seems unattainable, but with the SALEM printer we have an edge. C3DP manufacturing makes it possible to construct structures at around 10% of the cost of traditional brick laying and in a similarly reduced timeframe. For the purpose of this analysis we will assume that with the use of the SALEM C3DP concept it will be possible to erect the shell structure of a 20-Acre farm in no more than 6 months, as calculated in the previous section. This means that each SALEM printer will be capable of printing 2 Vertical Farms per year.

If we wish to calculate how long it would take to manufacture the entire 37 million facilities required to feed the world, we need to set a reasonable expectation for rate of manufacture for SALEM Printers. In terms of manufacturing complexity, the SALEM printer is roughly comparable to that of an electric vehicle and the Electric Vehicle manufacturer Tesla is a shining example of what can be achieved in terms of manufacture scaling when the demand and desire is great enough. Tesla ramped up from producing just 2,663 vehicles in 2012 to over 103,000 in 2017. This means Tesla averaged an increase of 20,000 cars to the manufacture rate per year.

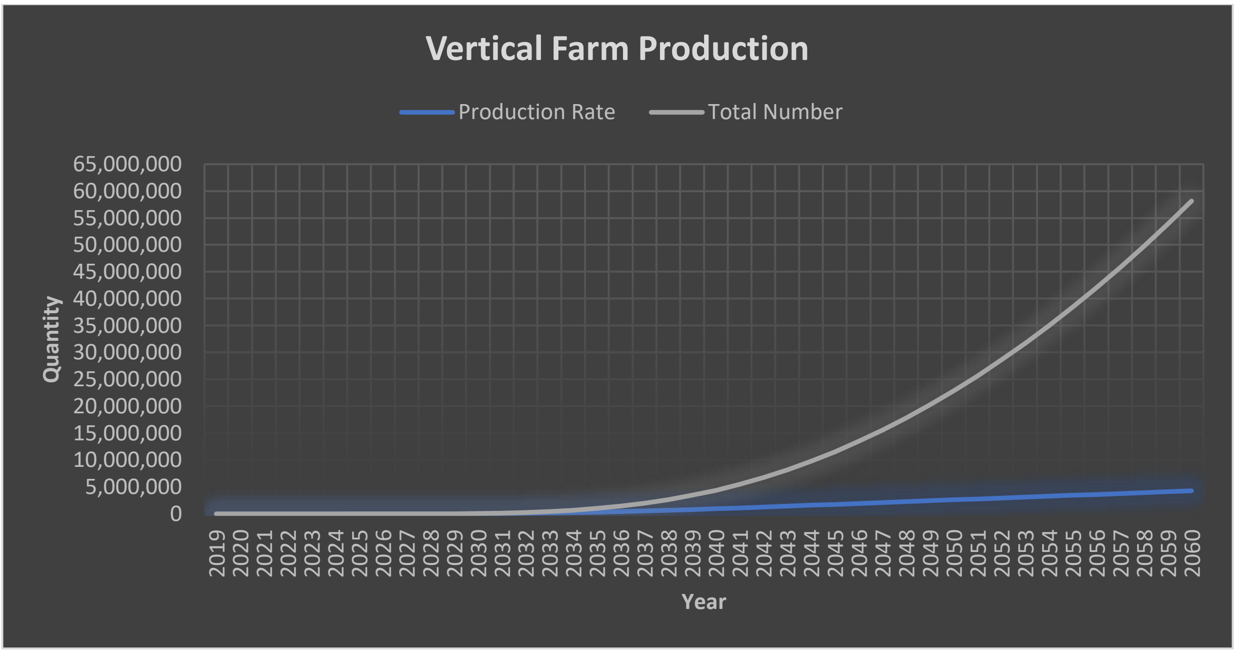
This is truly exceptional, and it is not reasonable to expect the same level of increase as the norm. We will instead assume that it will be possible to increase the rate of manufacture of SALEM printers by a more leisurely 6,000 units per year. This rate of increase will occur only after the end of the development period (2024) plus an additional 5 years of negligible productivity whilst the logistical framework and initial manufacturing facilities are generated. A final assumption is that each printer will have a life expectancy of 15 years. Below is a graph representing the SALEM production as described:



Graphical Representation of SALEM Printer production at an increase rate of +6000 PA

As you can see from this graph, under these assumptions on production rate, the total number of 'in service' SALEM printers would exceed 1,000,000 by 2047 and have reached over 2,000,000 by 2060, however the production rate will have only reached approx. 200,000 PA in the same timeframe. By 2045 we will have reached a production rate of 103,000 Printers PA. Tesla reached a production rate over 103,000 in 15 years from founding the company. Our example assumes it will take 26 years to achieve the same goal.

But if all these printers were used to produce Vertical Farms, at what point will we have manufactured enough to sustain the human population? Maintaining the assumption that each printer can produce 2 Vertical Farm Structures per year we can calculate and graph this as we have done for printer production and the result is as below:



Graphical Representation of Vertical Farm production at 2 Farms per year, per printer

For the data and calculations used to determine this, go to ***Appendix 6 – Planetary Vertical Farming***

Reading from this graph we can see that, with a reasonably modest ramp up rate of SALEM Printer production, it would be possible to have manufactured enough Vertical Farms to provide the entire planets food requirements by 2055, just 36 years after beginning the process, and for nearly half of that time the number of farms in service would be negligible.

Of course in reality, Vertical Farming is unlikely to replace traditional farming methods entirely. Despite only providing approx.18% of calories, livestock consumes as much as 83% of farmland [11] and it would still be impractical and somewhat morally questionable to raise and farm livestock in Vertical Farms. We could however, use Vertical Farming to produce the food required to feed livestock and move these types of farms to less naturally hospitable land, freeing more arable land for other purposes or to be reclaimed by nature. In any case, if Vertical Farming proves to be as profitable as projected in this analysis then the SALEM printer will undoubtedly help to pave the way for a sustainable human presence on Earth and beyond.

3.1.9 Business Deployment Plan

There are many feasible business strategies for generating Vertical Farms with SALEM Printers, the best route will depend on the end goal of the company. Regardless of the deployment method, If the end goal is to make an early return on investment into the SALEM Printer then Vertical Farming is not the best path to fast profitability. Vertical Farming, through the SALEM Printer, will be a long-term investment but one with profound results for all that are willing to wait for the seed to grow. Below we will examine some example deployment methods. This is by no means a comprehensive study; the main purpose is to demonstrate that Vertical Farming as a concept can be feasibly deployed.

Government sponsored

If the main intent is to deploy Vertical Farms on a large-scale, government sponsorship will likely be the most structured route. In this scenario Governments would sub-contract the SALEM Manufacturer to construct Vertical Farms across the respective country as a policy to provide the people with access to social food produce. This is one of the better options for fast growth in terms of deployment but will likely be less lucrative then retaining ownership of farms after completion of construction.

Membership Based

In this scenario, the printers and Vertical Farms are owned and run by the SALEM Manufacturer and consumers pay a membership fee to have access to the produce. The main downsides to this are financial reasoning. It would require a high level of investment initially and would take some time after completion for the Vertical Farms to become profitable. This means that initial growth would be relatively slow until farms begin to return a profit.

Direct sale

The simplest route to profitability for the SALEM Printer is for direct commercial sale. In this business model, the SALEM Manufacturer produces SALEM Printers and sells them as a tool for construction companies and tradesman. This method would be unlikely to lead to Vertical Farming on its own as the applications for SALEM Printing in construction are virtually limitless. For direct sale to enable the creation of Vertical Farms, the Vertical Farm must be the product being sold.

Direct ownership

The next simplest deployment method is for the SALEM manufacturer to manufacture Vertical Farms and directly own and maintain them. All produce is sold on the free market in direct competition with traditional farms and adoption will depend on consumers choosing to transfer to vertically farmed produce on their own accord. This deployment method would be one of the slowest in growth as the SALEM manufacturer would initially need to invest large amounts of money and resources to establish the farms and these farms would take potentially over a decade each to begin turning a profit.

Scaled for home (<1 acre)

If the scale of the farm is reduced to a more personal level it would be possible to enter the commercial market with direct sales by providing the manufacture of Vertical Farming facilities that are scaled for personal use. Due to the massive reduction in labour and secondary manufacture requirements, the SALEM Printer would make the construction of permanent structures ten orders of magnitude cheaper than today a reality. Self-sufficiency conscious individuals could purchase small scale Vertical Farms as a means of supporting their family as we do today with greenhouses, but on a more meaningful level. A personal Vertical Farm in this context is a farm that is less than 1 acre in total growing area. Personal farms would generally be less than 3 stories high and high density.

As an example, for a cylindrical facility that has a diameter of 5 meters and is 2 stories high and each floor is stacked 3 times with crop will have approx. 0.024 Acres of crop space. If we assume, we can yield 30,000lbs of food per year from an acre of land, this farm would be capable of producing approx. 730lbs of food per annum. For a family of five omnivores this would generate enough crop produce to provide all year, outside of meat and dairy. A Vertical Farm of this size can be managed easily and sustainably for just the cost of water, electricity and a few hours a week of care.

Thanks to savings in structure construction costs, a fully autonomous farm of this size could be brought to an affordability level similar to purchasing a new car, although purchasing a personal Vertical Farm should be viewed as an investment similar to switching to personal solar power generation. The farm would reduce the household cost of groceries by approx. $2000 PA and provide security and protection from fluctuating markets, as many places around the world depend heavily on imported produce. Communities could also pool fund smaller facilities and share the produce and labour.

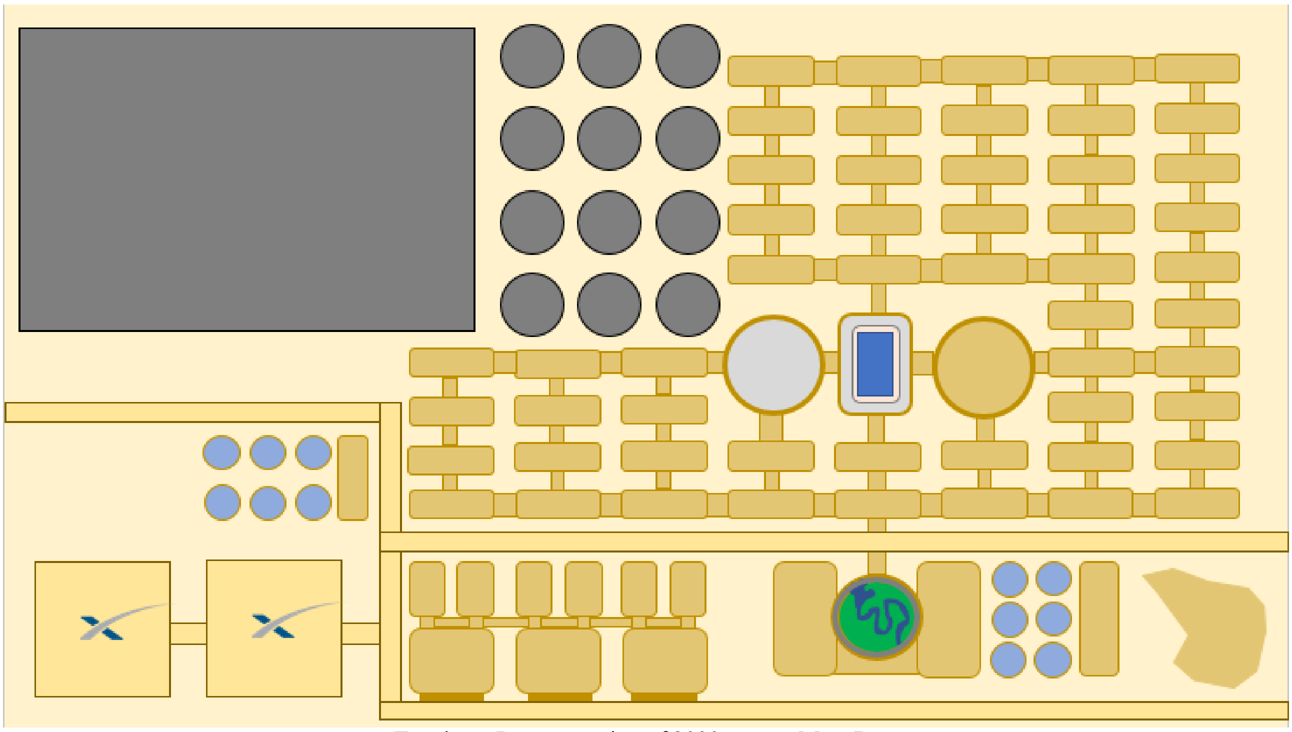
Construction Rental

The SALEM manufacturer produces a fleet of printers that are leased out to other construction companies and private enterprises for the purpose of constructing Vertical Farms. In this Scenario the SALEM Manufacturer provides the SALEM Printer only and is not involved in the manufacturing process of the Vertical Farm. This method would be the least effective for bringing about the advent of Vertical Farming but would also be the least financial risk as the only development required would be the SALEM Printer itself and not an entire Vertical Farming facility.

Contract Build

Contract building in this example means to use the SALEM Printer to fulfil private contract construction of Vertical Farms. Interested private parties would pay for the SALEM manufacturer to construct the Vertical Farm. Contracts could differ from constructing the shell structure only, to providing a fully operational Vertical Farm, complete with staff and maintenance. By providing continuous aftercare and maintenance of the facilities the SALEM manufacturer would grow proportionally to the number of facilities providing long term stability and making this the most viable business deployment plan.

3.2.0 Application Analysis - Mars Base



Top down Representation of 2000-person Mars Base

3.2.1 Introduction

The ultimate prerogative of space exploration is to establish a permanent human presence on other celestial bodies outside of Earth such as Mars. While enormous progress has been made in technology that enables us to travel to these destinations, not much has been publicly declared on how humans might survive long term after arrival.

The SALEM Printer aims to demonstrate a route to feasibly building permanent structures on distant worlds. SALEM would significantly reduce the time it takes to generate full structures on Mars and drastically shrinks the required crew size to build a single base. As SALEM needs only water, cement, aggregate and electricity to function, all the physical materials required can be acquired or produced easily at location. This means the load that needs to be transported from Earth is greatly reduced narrowing the cost of failure and broadening the rewards of success.

In this chapter we will examine the process of building a permanent 2000-person capacity base on Mars using SALEM printers with the intent of drawing conclusions on feasibility, cost, timeframe and risks to achieving this goal.

3.2.2 Requirements

This project is intended to establish a 2000-person capacity base on Mars with the primary prerogative of providing proof of concept of sustainable living on Mars. It should be located close to a significant source of water and provide prospects for mining mineral and ore to allow for future expansion beyond the initial base to a city of up to 1 million people. The project assumes that by launch date the Starship (BFR) would be completed and operational. It also assumes that the SALEM Printer is developed and proven.

The initial cargo to Mars must be transportable in no more than two Mars transit cycles and require no more than 15 Starships to establish self-sufficiency. The base will provide all the necessities for survival such as food/water production, shelter and stable electricity, as well as many basic comforts such as clothing manufacture, communal spaces, entertainment and exercise facilities. The base should be established and self-sufficient by the next trajectory cycle, or approx. 26 months post launch. This is to enable human occupants to be transported at the next available opportunity with the reassurance that there is accommodation and the means of survival upon arrival.

A key success factor of this project is that most of the materials required to create the base is procured on-planet. It is therefore essential that Silicon, Calcium, Iron, Magnesium and Aluminium are easily accessible to manufacture the cement and aggregates that will be used to print the structures, as this constitutes the vast majority of the material mass of the project. Delivering large quantities of Cement to Mars would severely stunt the scalability of the base and would result in a much greater investment of Starship Rockets to complete. Luckily, it would seem these elements happen to be some of the most abundant in the Martian crust. UniverseToday.com (2015) states:

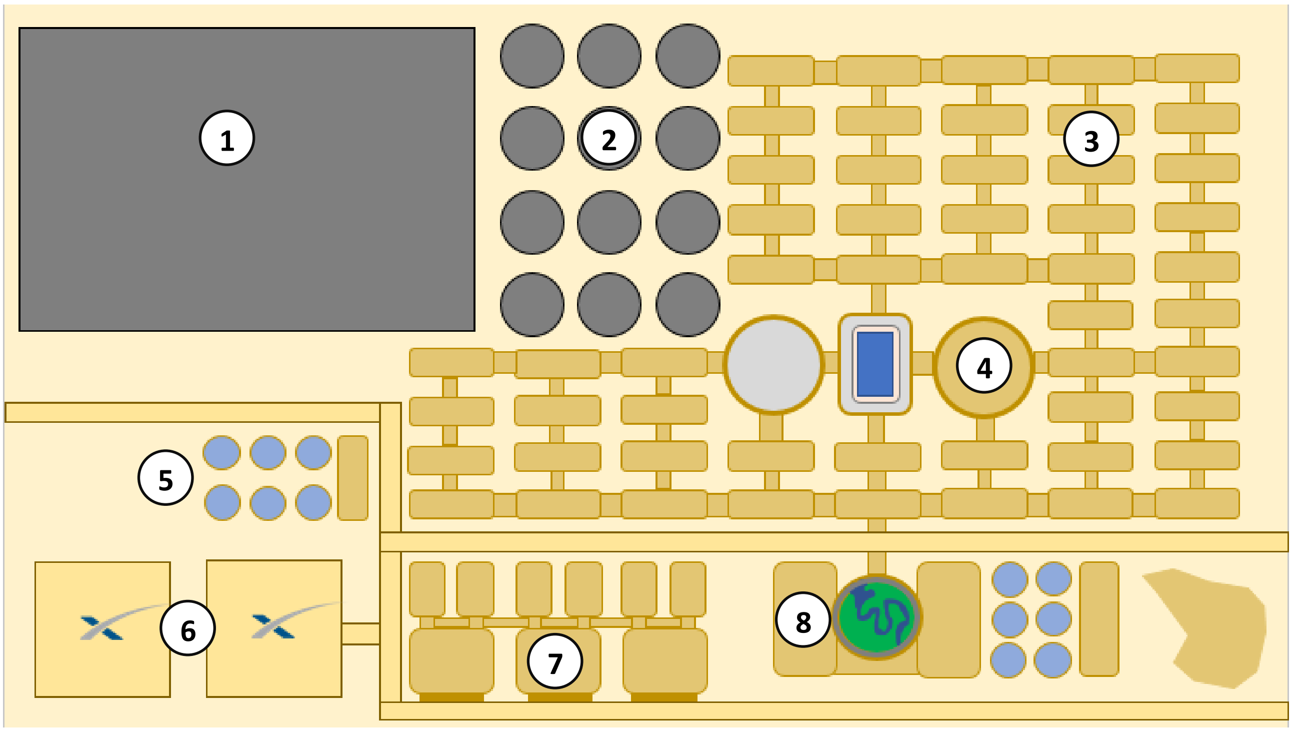
"Besides silicon and oxygen, the most abundant elements in the Martian crust are iron, magnesium, aluminium, calcium, and potassium. Oxidation of the iron dust is what gives the surface its reddish hue." [12]

All structures must be connected via a series of channels and tunnels to prevent the need to wear a life support suit unless leaving the base. The base must also have foundries for smelting metal and glass as well as for forging and grinding cement. The base must have shared facilities for exercise; such as swimming and running, communal/social areas and medical facilities capable of managing an array of ailments and emergencies.

Mars Base Requirements Summary

No	Requirement
1	Must sustain at least 2000 individuals
2	Must take less than 1 trajectory cycle to complete
3	Must not require resources sourced off-planet after completion
4	Must provide sustainable food production
5	Must acquire all energy through sustainable means
6	Should require no more than 15 Starships (BFR) to establish
7	Must have access to easy mining of Silicon
8	Must have access to easy mining of Calcium
9	Must have access to easy mining of Iron
10	Must have access to easy mining of Aluminium
11	Must have access to easy mining of Magnesium
12	Must have access to easy mining of Water
13	Must be capable of producing cement
14	Must have the means of clothing production
15	Must have at least 1 community swimming pool
16	Must have smelting capabilities for iron, glass and cement
17	Must have at least 1 jogging track
18	Must have at least 1 communal recreation space
19	Must have at least 1 medical facility

3.2.3 Proposal



Annotated top down Representation of 2000-person Mars Base

With the SALEM Printer it should be possible to establish a permanent presence on Mars in an extremely short timeframe with just a handful of Starship launches and a skeleton construction crew. It could take as little as 20 personnel to build a 2000-person base on Mars and the Mission will be accomplished by taking advantage of Mars' natural resources as much as possible to reduce the burden of launching cargo.

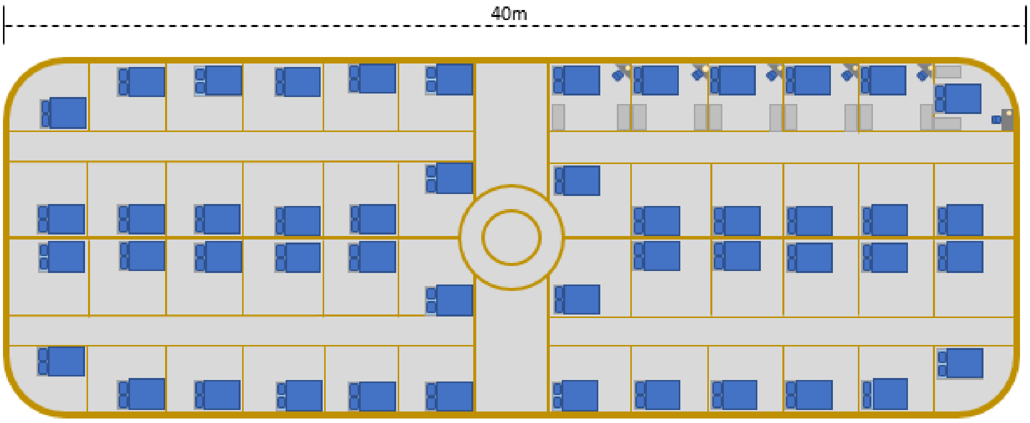
No	Name
1	Solar Array
2	Vertical Farms
3	Living quarters and factories
4	Entertainment and Recreation Facilities
5	Chemical Processing Facility
6	Landing Zones for Starships
7	Foundries
8	Grand Hall

3.2.3 Base Specification

From the high-level requirements, we can envisage a base with a certain number and variety of buildings. These range from accommodation for the occupants, Foundries, Water & Fuel processing facilities, Machining Workshops, Forges, Vertical Farms, shared facilities such as swimming pools and Libraries and Healthcare facilities. For the sake of reducing structure complexity, risk of an issue arising during construction and the need to deliver an excessive amount of building materials to Mars, all structures will be single story for this assessment bar the Vertical Farms.

The Base will also need to feature at least two landing platforms for Starships to land, a Solar Array for electricity production and will have at least one road leading through the base from East to West for easy access to the Mars wilderness and to improve transportation of raw materials in and out of the base.

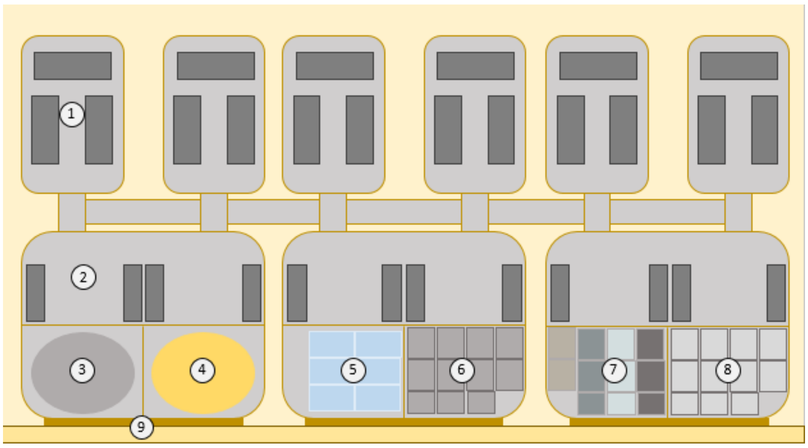
Housing



Representation of A 20 Meter by 40 Meter printed dormitory

Housing facilities have been envisaged as 40-meters by 20-meter structures that are each capable of housing up to 48 individuals, meaning the total number required to house 2000 people would be 42. These structures will be entirely manufactured using the SALEM Printer, including inside walls and room furniture and will connect to other domiciles via either tunnels or 3D Printer concrete corridors.

Foundries

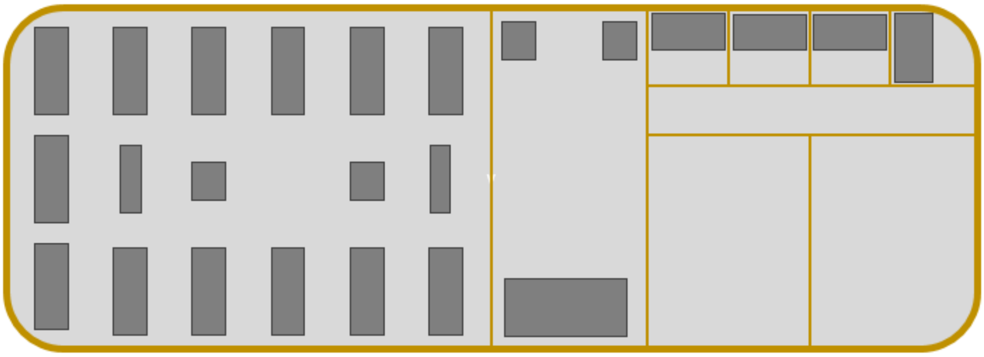


Representation of the Mars base foundry

No	Name
1	Smelting/Forging Chamber
2	Forming Workshop
3	Cement Storage
4	Aggregate Storage
5	Glass Storage
6	Iron Storage
7	Uncommon Ingot Storage
8	Aluminium Storage
9	Truck Access Door

Smelting and forging facilities must be available at the base in order to produce metal ingots, cement and glass to provide materials for future expansion and resolving challenges during construction. The illustration above shows three smelting facilities. Each facility is 40 meters in width and 70 meters in length and features two smelting and forging chambers, an area for secondary forming and two storage rooms that are accessible to trucks. Between the three facilities cement, aggregate, glass, iron, aluminium and a mix of other metals are produced. The facility structures will be 3D printed using the SALEM Printer, including interior walls and features specific for smelting such as a ventilation system and furnaces.

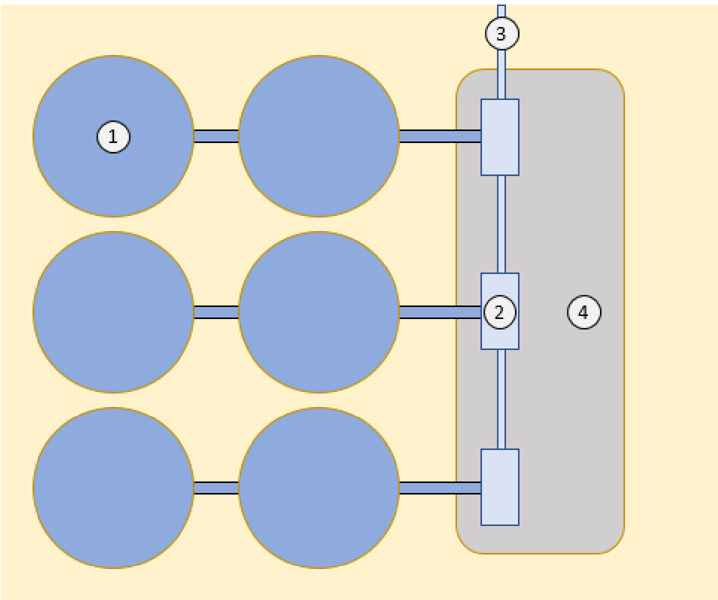
Workshops



Representation of a 3D Printed Machine Workshop for the Mars base

Workshops for manufacturing metal parts is an absolute must for a self-reliant community. For a community of just 2000 people, a handful of machines would likely suffice so the example base has one 40x20m structure for metallurgic workshop and another structure of the same size for assembly and storage of manufactured components. Outside of metallurgy there will also need to be a workshop for manufacturing clothes, and a workshop for computer aided activities bringing the total 40x20m structures for workshop activity to four.

Chemical Processing Facilities



No	Name
1	Fluid Containment Silo
2	Chemical Processing Unit
3	Exit Feed
4	Chemical Processing Facility

Representation of A Mars base Chemical Processing Facility

There will need to be at least two chemical processing facilities at the Mars base. The first is for water storage and treatment for human consumption and for feeding the Vertical Farms. The basic facility will feature 6 silos for fluid storage. These will be formed through 3D printing concrete with the SALEM Printer and will have channels designed within the walls to allow hot air to pass through and heat the water passively. This water is fed into the facility where it is processed and then pumped out to the rest of the base through pipes laid underground. One 6-silo facility should be enough to provide for all 2000 residents. The second chemical facility will process rocket fuel to allow the community to reuse the rockets used for transporting cargo to return to Earth.

Community Facilities

There will be various facility requirements for maintaining the comfort and survivability of the base's community from basic needs such as washrooms and cooking facilities, to purely social facilities such as cinemas, libraries and virtual reality rooms. The total structures for community purposes are as follows:

Facility	Structure Size	Quantity	Comment
Washroom	40 x 20	4	For Bathing and Toilets
Canteen	40 x 20	3	For providing cooked meals and a space to eat and relax
Dining Hall	**40∅**	1	For providing cooked meals and a nice space to eat
Grand Hall	100 x 60	1	An indoor park, running track, library and cinema
Swimming Pool	40 x 60	1	For fitness and therapeutic relief
Entertainment Centre	**40∅**	1	VR centre, gaming lounges, Bars and communal spaces as well as a medical centre

Vertical Farms

The Base will also feature a set of Vertical Farm facilities to provide the food to sustain the community. It has been assumed that each facility will have an overall grow area of 20-Acres and 1 Acre can provide for 10 people. 12 of these Vertical Farms should be constructed to provide a total of an equivalent of 340 acres of arable land. This should be enough capability to provide for up to 2,400 people giving some margin of error.

3.2.3 Total Facilities

To summarise, there is a requirement for a total of 74 significant structures to be built to establish a self-sufficient 2000-person base on Mars.

Facility	Structure Size (m)	Quantity
Dormitories	40 x 20	42
Smelting Foundry	40 x 70	3
Vertical Farm	**30∅**	12
Water Processing Facility	6 Silo (**15∅**)	1
Fuel Processing Facility	6 Silo (**15∅**)	1
Workshop (Metal, Clothes & CAD)	40 x 20	4
Washroom	40 x 20	4
Canteen	40 x 20	3
Dining Hall	**40∅**	1
Grand Hall	100 x 60	1
Swimming Pool	40 x 60	1
Entertainment Centre	**40∅**	1

If we assume that all single-story buildings (all but Vertical Farms) in this list can be constructed in 30 days or less using the SALEM Printer and a single Vertical Farm will take 180 days or less to print, then the total number of printers we will need to complete the base within one Mars year is:

$$\frac{(62 \times 30) + (12 \times 180)}{687} = 5.85$$

3.2.4 Cargo Requirements

To determine how to deploy this base we need to ascertain the resources that are needed from Earth. The base must not require resources sourced off-planet once completed so the largest cargo expense should be on machinery and tools. Resources such as cement, aggregates, glass and metals should be sourced and produced on Mars as much as is practical. To reduce mission risk a temporary base should be included in the cargo requirements. This temporary base must provide the minimal requirements for the construction crew for up to 1 Martian year.

Other factors to consider are mining, smelting, forging and secondary manufacture machinery that will make it possible for the Mars base to expand and replenish its own resources. There will also be a large mass overhead to consider with electronics and electrical components such as solar tiles, battery storage, full spectrum LED lighting and hydroponic control equipment. This is because these items will not immediately be manufacturable on Mars and it may take many years to establish at all on-planet. For the purpose of this analysis, manufacture of these items will not be established as part of the 2000-person base project.

3.2.4 Initial Base and Crew

As there will be a few weeks of setup time before first printed structures are constructed on Mars, there is a need to bring along a certain level of temporary survival equipment for the construction crew to utilise. This includes food, water, shelter and personal affects.

Food & Water

If we assume that enough food should be sent to Mars for a 20-person crew to survive for 1 Mars year and that each person will require a total of 1,711Kgs (3,764lbs) of food for the year, the total mass to be sent is 34,222Kg (75,288lbs). If we also assume that it will take as long as the entire year to set up water mining and processing facilities and each person requires 2 litres of water per day, then the total amount of water we will need to deliver is:

$$Total\ Cargo\ Water = Time \times water\ consumption\ rate \times crew\ size$$
$$Total\ Cargo\ Water = 687 \times 2 \times 20 = 27{,}480ltr$$

One litre of water is equal to 1 kilogram, so the total weight of water that needs to be delivered for the mission is 27,480Kg.

Shelter

There are a lot of factors to consider to determine the exact weight of the temporary shelter as there are still many unknowns. If we make a broad assumption that each person requires $16m^2$ of space for shelter as an average, then the entire 20-person crew would need a space of approx. $320m^2$. If we also assume that the initial temporary shelter will be as sturdy and heavy as a lightweight mobile office, then we can draw some conclusions about what a sensible weight for the shelter would be. A 40 foot (12.2m) by 12 foot (3.7m) Steel-clad portable cabin produced by Elliot weighs 3,409kg (7,500lbs) [13]. To find the number of these portacabins it would take to house the crew we can divide the required area by the area of the portacabin.

The area of the portacabin is:

$$12.2 \times 3.7 = 45.14m^2$$

So, the required number of portacabins will be:

$$\frac{320}{45.14} = 7.08$$

Taking 3,409Kg as our weight for one portacabin and number of cabins required as 7, we can determine the total weight of the shelter to be 23,863Kg (52,498lbs). This weight assessment does not include the weight of life support items such as oxygen, heating and pressure systems. For the sake of ease, we will assume that these items add a further 10,000Kgs to the package weight bringing the total weight for the temporary shelter up to 33,863Kg.

Personnel & Transit Accommodation

A 20-person strong team of individuals will be required to complete the 2000-person Mars base so there will be some considerations to make for transporting the personnel from Earth to Mars. The journey will take approx. 150 days to complete so the ship must provide enough space and facilities for the comfort of the 20 individuals for the entire journey. Food and water will also need to be provided for the entire journey.

If we assume that the physical accommodation will be similar in respect to weight to the shelter discussed previously, we can expect a basic weight of approx. 34,000Kg. There will need to be some communal entertainment during the trip as it is such a long journey. An allowance of 10,000Kgs would be ample for shared devices such as television, electronics, fitness equipment and furniture. If each passenger, on average, weighs 80kg and has 100kg of personal affects then the total passenger weight would be 3,600Kg. Taking 910Kg to be the food requirements of one person for one Earth year we can calculate the required food for the journey as:

$$Food\ Weight = \left(\frac{Food\ PA}{Days\ PA} \times Transit\ Time\right) \times No\ Passengers$$

$$Food\ Weight = \left(\frac{910}{365} \times 150\right) \times 20 = 7{,}480Kg$$

If 2 litres of water per person is required per day, for 150 days one person would consume 300ltr of water. For the whole crew the total water consumption for the transit would be 6,000ltrs for a total weight of 6,000kgs. The total weight of personnel and transit accommodation is the combination of personnel, transit accommodation, entertainment, food and water. For our example this is:

Cargo Requirement	Weight (Kg)
Transit Food	7,480
Transit Water	6,000
Transit Vessel	34,000
Entertainment and Comfort	10,000
Personnel & Personal Effects	3,600
Total	**61,080 Kg**

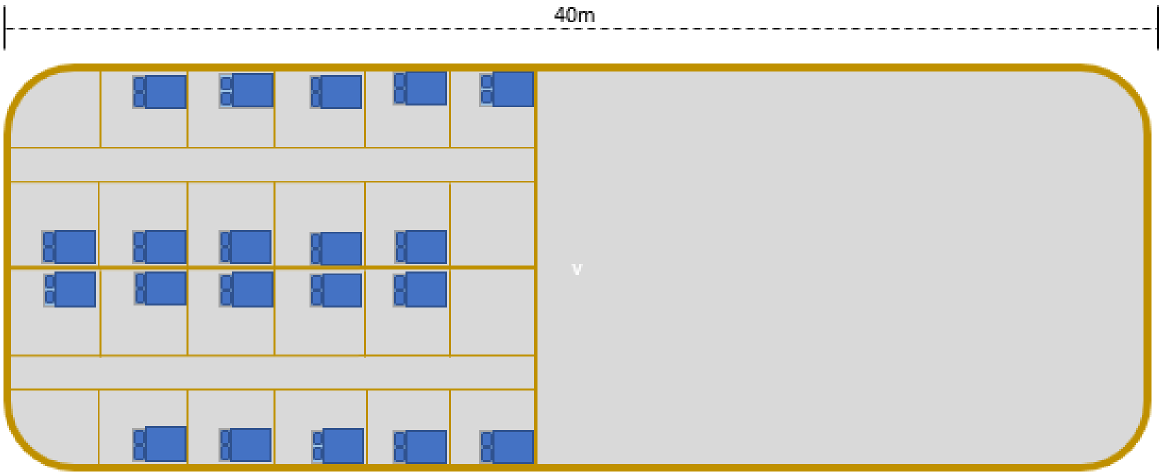
3.2.4 Structure Construction Equipment

SALEM Printers

The SALEM Printer is an essential element to the success of establishing a 2000-person capacity base on Mars as it allows the endless expansion of the base with only electricity and raw materials. In the base specifications section above we calculated that at least 5.85 SALEM Printers would be required to print the entire base in one Mars year. If we assume 7 will be sent this gives us some redundancy. We defined in the design proposal that one fully equipped SALEM Printer would weigh approx. 3,025.4Kg so for 7, the total printer weight would be 21,177.8Kg.

Cement

The first structures that will be built will ensure that the construction crew can live self-sufficiently on Mars. This is so that if anything happens to the mission after the construction crew has been sent, such as a failed supply rocket launch, the crew will be able to survive until the next available rendezvous. One 40 meter by 20-meter structure would provide enough space to comfortably house a 20-person crew.



Representation of A 20 Meter by 40 Meter 3D Printed Living Space

In order to continue indefinitely on Mars, the crew must manufacture a means of mining and processing water, as well as producing crops to eat and a means to manufacture cement for expanding the base. Three more buildings of the same dimensions as the housing structure would provide enough space to achieve this. If we assume that cement for these initial buildings would need to be delivered from Earth, we can calculate the cargo requirements. The amount of cement required would be approximately 15% of the total mass of the buildings. We can express this for a rectangular building as the formula:

$$Cement\ Mass = (Wall\ 1 + Wall\ 2 + Wall\ 3 + Wall\ 4 + Floor + Ceiling) \times 0.15$$

We know that for our buildings that opposite walls will be the same size so for each wall size:

$$Building\ Mass = L \times W \times D \times \rho \times \Delta$$

$$Wall\ Size\ 1\ Mass = 40 \times 2.5 \times 0.1 \times 2400 \times 0.15 = 3{,}600Kg$$
$$Wall\ Size\ 2\ Mass = 20 \times 2.5 \times 0.1 \times 2400 \times 0.15 = 1{,}800Kg$$
$$Floor/Ceiling\ Mass = 40 \times 20 \times 0.1 \times 2400 \times 0.15 = 28{,}800Kg$$

The total cement mass for each 40 x 20m building is therefore:

$$Total\ Cement\ Mass = (3{,}600 \times 2) + (1{,}800 \times 2) + (28{,}800 \times 2) = 68{,}400Kg$$

If we times this mass by 4 we find the total Cement requirements from Earth for the initial printed structures is in the region of 273,600Kg.

Pressure Doors

The Martian atmosphere hovers around 0.6% the pressure of Earths, meaning that all buildings must be pressurised. For safety, if a building is damaged and begins to leak there must be pressure lock doors at all exits and entrances. If we assume that each building will have on average two entrance/exit points, then we will require a total of 148 pressure lock doors for the entire base. Assuming each door weighs 120Kgs, we find that the total weight for doors will be approx.17,760Kg.

3.2.4 Power Generation & Storage

The Base is intended to initially be powered by a Solar Array and power will be stored through Tesla Powerwall cells. Initially the base will not have the facilities to manufacture Solar Cells or Battery Packs so these will need to be delivered from Earth to Mars. The power station must produce enough electricity to power at least ten 20-acre Vertical Farms and all the lighting, heating, air conditioning and electronics of the base. If we assume that the base will have a total power rate of approx. 6MWh and a single 12W cell weighs 267 grams, we can determine the number of solar cells with the following formula:

$$Solar\ Array\ Mass = \left(\frac{Energy\ Requirements}{Cell\ power\ rate}\right).Cell\ Weight$$

$$Total\ Mass = \left(\frac{6{,}000{,}000}{12}\right).0.267 = 133{,}500Kg$$

Vertical Farms will use power generated by the Solar Array in the day and will drastically reduce power needs at night when the farm lights switch off. At night the Base will rely on a battery system for power. A single Powerwall cell can store 13.5kwh of power. If it takes 1Mwh of power to run the base at night and there are 12 hours a day without sunlight and hence no power generation, then the total number of Powerwall Cells we need is:

$$No\ Cells = \frac{Power\ Rate \times Time}{Cell\ Capacity}$$

$$No\ Cells = \frac{1{,}000{,}000 \times 12}{13{,}500} = 889$$

Each Cell weighs approx. 97Kg so total battery pack weight will be: $889\ Cells \times 97Kg = 86{,}233Kg$

3.2.4 Metallurgy

Mining Equipment

Mining is a key component of survival on Mars and as such will be a priority for any early missions to the planet. Mining will be pivotal to acquiring water, expanding the base and returning home. The initial crew will need the means to mine thousands of tons of aggregates for the construction of permanent structures, as well as ores such as iron, copper, sulphur, aluminium, calcium and silicon; all abundant on Mars. In the Cement section we calculated that one 40-meter by 20-meter building would use 68,400Kg of Cement and that cement made up 15% of the total mass of the building. We can calculate the total overall mass of the structure using:

$$Total\ Building\ Mass = 68{,}400 \times \frac{1}{0.15} = 456{,}000Kg$$

If we assume that one 40 x 20m building constitutes approx. one hundredth of the total mass of the base then the total raw materials, we will need to mine will be:

$$Total\ Base\ Mass = Building\ Mass\ \times Total\ No\ Buildings$$
$$Total\ Base\ Mass = 456{,}000\ \times 100 = 45{,}600{,}000Kg$$

A similar amount of water will also need to be mined for mixing the cement and for survival. To keep the assessment simple, we will assume that with water, aggregates, cement materials and ore mining, the Mars construction crew will need to mine a total of 90,000,000Kg, or 90,000 Tons. If we maintain the requirement of completing the base within 1 Martian year of touchdown to enable settlers to arrive at the next transit cycle, then the construction crew must be able to mine an average of 132,750Kgs per day. To achieve this level of mining we will need to utilise a combination of rock blasting and excavation equipment. Assuming each excavator, crusher and truck can process 30 tons of material per day, we can find the total mining equipment requirements. Equipment models have been taken from the Cat catalogue for weight purposes only. Actual vehicles used will likely be bespoke to Mars:

Item	Weight (Kg)	Quantity	Total Weight
CAT 725C2 Articulated Truck	23,040	5	115,200
CAT 320 Hydraulic Excavator	22,500	5	112,500
CAT 320 Rock Drill Attachment	6,100	10	61,000
CAT MD6250 Rock Drill	21,000	3	63,000
CAT P235 Pulveriser Attachment	3,421	10	34,210
Hand Power tools	50	100	5,000
Total Mining Equipment Weight			**390,910Kg**

Smelting and Forging Equipment

The SALEM printer will be utilised as much as possible to reduce cargo mass, this includes producing basic foundries for smelting materials and storage tanks for water, fuel and food. The materials for metallurgy from Earth should only be highly processed items that cannot be easily sourced or manufactured on Mars. For a basic smelting foundry, the key items required from Earth would include motors to control the circulation of air through the forge and hand tools for forging ingots into basic shapes. The cargo expense for this aspect should therefore be relatively small so an allowance of 10,000Kg would also afford the opportunity for secondary forming equipment to be shipped too.

Tools & Machinery

In order to create useful items from metals produced on Mars, we must deliver various secondary forming machinery as part of the cargo. These tools and machines will provide the bases occupants with the power to dynamically deal with challenges faced during construction and manufacture solutions as and when required. In the long term, these tools and machines must be capable of producing all the parts necessary to reproduce the tools themselves, allowing the base to grow its capacity to manufacture without relying on shipments from Earth. For the purpose of the 2000-person base example, the following assumptions have been made on secondary manufacturing cargo requirements:

Item	Weight (Kg)	Quantity	Total Weight
Turning Lathe	1,000	4	4,000
Milling Machine	1,500	4	6,000
CNC Machine	2,000	4	8,000
Pillar Drill	500	4	2,000
Grinding Pillar	500	4	2,000
Sheet Metal Press	2,500	4	10,000
Welding Booth	500	4	2,000
Power Tools (hand)	10	200	2,000
Hand Tool	5	500	2,500
Total Tooling Weight			**38,500Kg**

3.2.4 Transportation

Personnel should have the capability to safely travel at least 50 km from the base in search of resource deposits. It is therefore necessary to include a portion of cargo space for transport vehicles. The specific transport vehicles are yet to be distinguished and will likely be bespoke designed for Mars application. If we broadly assume that these Mars vehicles will on average weigh 2,000Kg and up to 5% of the base may be on a mobile mission at any given time then the total weight of transport would be:

$$Total\ Transport\ Mass = Vehicle\ Weight \times No\ People \times Usage\ Rate$$
$$Total\ Transport\ Mass = 2{,}000 \times 2{,}000 \times 0.05 = 200{,}000Kgs$$

3.2.4 Electronics

For the Base to become entirely independent and self-reliant, it must provide a means of manufacturing food. As the natural Mars atmosphere is inhospitable to life as we know it, all agricultural activities will need to be done indoors and as a result, artificially. Vertical Farms provide a solution to the agricultural challenge however, these facilities will require a large payload from Earth to achieve due to the need for LED Lights and hydroponic control equipment.

Lighting

In ***Appendix 4 – Farm Energy Consumption & Production*** we calculated that we would need 12,681 LED Lights to power a 20-Acre farm and we will have a total of 12 farms in our hypothetical base. This means we would need a total of 152,172 70W LED lights to power the farming needs of the Base. If we assume that the weight of a single LED light can be reduced to 300 grams, then the total weight of the LED farming lights would be 45,651.6Kg. Additionally, there will be approximately 100 other structures on the base which will also require lighting. If we assume that each building will require a further 50 lights, then an additional 5,000 lights will need to be shipped. If these also weigh 300 grams then the total additional weight of lights would be 1,500Kg. If we also assume that approximately 5,000Kg of electrical cable will be required to wire the base then the total lighting cargo weight would be 51,651.6Kg.

Farming equipment

On top of the cargo for farming lights, a single Vertical Farm would also require 30 Water Pump and Filtration Systems as well as 30 Air Conditioning Systems. If we assume a single water system weighs 30Kg and a single air conditioning unit ways 50Kg then the total weigh for each would be:

$$Total\ Accessory\ Weight = No\ per\ Farm \times Weight \times No\ of\ Farms$$
$$Total\ Water\ Pump\ Weight = 30 \times 30 \times 12 = 10{,}800Kg$$
$$Total\ Air\ Con\ Weight = 30 \times 50 \times 12 = 18{,}000Kg$$

We will assume for this assessment that all other hydroponic equipment such as trays, plumbing system and racks will either be formed using the SALEM Printer or manufactured on planet.

Consumer Electronics

Each passenger has been given a personal cargo allowance of 500Kgs. It has been assumed that a part of this allowance would go to personal computers, televisions, games consoles and other consumer electronics, however there will also be communal computers and electronics utilised throughout the base for various reasons. Each building is given an allowance of 500Kg for additional electronics which raises the total consumer electronics weight up to 35,000Kgs

Motors and Spare Parts

The aim of the base is to be self-sufficient and eventually not have to rely on cargo delivered from Earth. By providing components like Motors, transformers, resistors, signal relays, capacitors, solenoids and a whole other array of basic electrical parts the base occupants can manufacture complicated tools and equipment as the need arises. An accessory box with 1000 Motors of varying sizes and electrical components to go with it would be invaluable to a budding colony. A budget of 40,000Kgs should be made for this purpose.

3.2.4 Total Cargo Requirements

The total cargo requirements to construct a 2000-person capacity, permanent base on Mars would be roughly equal to the summation of all the load factors discussed in this chapter. With this information we can draw a conclusion on how many Starship rockets would be required to complete the project.

Cargo	Total Weight
Initial Base Food	34,222
Initial Base Water	27,480
Initial Shelter	33,863
Personnel & Transit	61,080
SALEM Printers	21,177.8
Cement	273,600
6MWh Solar Array	133,500
1MWh Energy Storage	86,233
Mining Equipment	390,910
Tools & Machinery	38,500
Transportation	200,000
Lights & Electronics	130,451
Pressure Lock Doors	17,760
Motors and Spare Electronics	40,000
Total Cargo Weight	**1,488,776.8Kg**

If we assume that a single Starship will be capable of transporting up to 100,000Kg to Mars then we can find the total number of Starships required to transport our Mars base cargo by dividing the total Cargo weight:

$$Req'd\ No\ Starships = \frac{Total\ Cargo\ Weight}{Max\ Payload}$$

$$Req'd\ No\ Starships = \frac{1{,}488{,}776.8}{100{,}000} = 14.9$$

3.2.5 Deployment Strategy

Dependant on the accuracy of this assessment, it could be possible to establish a permanent 2000-person base on Mars with as few as 15 Starships. The most rational way to deploy this would be to send several automated Starship Rockets to deliver the bulk of the cargo in one Mars transit cycle followed by a final number of Starships that carries all the temporary supplies such as dry packed food and water, temporary shelter and the construction crew. Once the base has complete self-sufficiency in energy, food and water production a second wave of Starships can be sent with settlers and additional tertiary manufactured items to continue base growth.

After self-reliance has been established and the new settlers have arrived the focus will move toward stable growth. SALEM Printers will be used to continually increase available operating space, whilst the metallurgy and manufacturing workshops will focus efforts on producing tools to expand manufacturing capabilities to include Photovoltaic Cell production, LED Lights and composite materials. When the base can manufacture solar cells and LED lights it can expand food production capabilities with new Vertical Farms which ultimately means more settlers can join from Earth or natural births on Mars can begin to occur.

3.2.5 Cargo Distribution

Now we have worked out how many payloads we will need to send to Mars to establish the base, we need to decide a rational way of distributing the cargo between Starships. The cargo should be distributed such that if any single spacecraft fails, the mission can continue at a slightly reduced capacity. The humans that construct the initial base will naturally be at great risk of life and should therefore only journey once all tools and materials to establish a permanent presence has arrived. For this reason, it makes sense to send the bulk of non-human cargo a transit cycle earlier than the launch with humans aboard, allowing time for data to be received about the landing coordinates and condition of the cargo and plans to be amended for maximum chance of success.

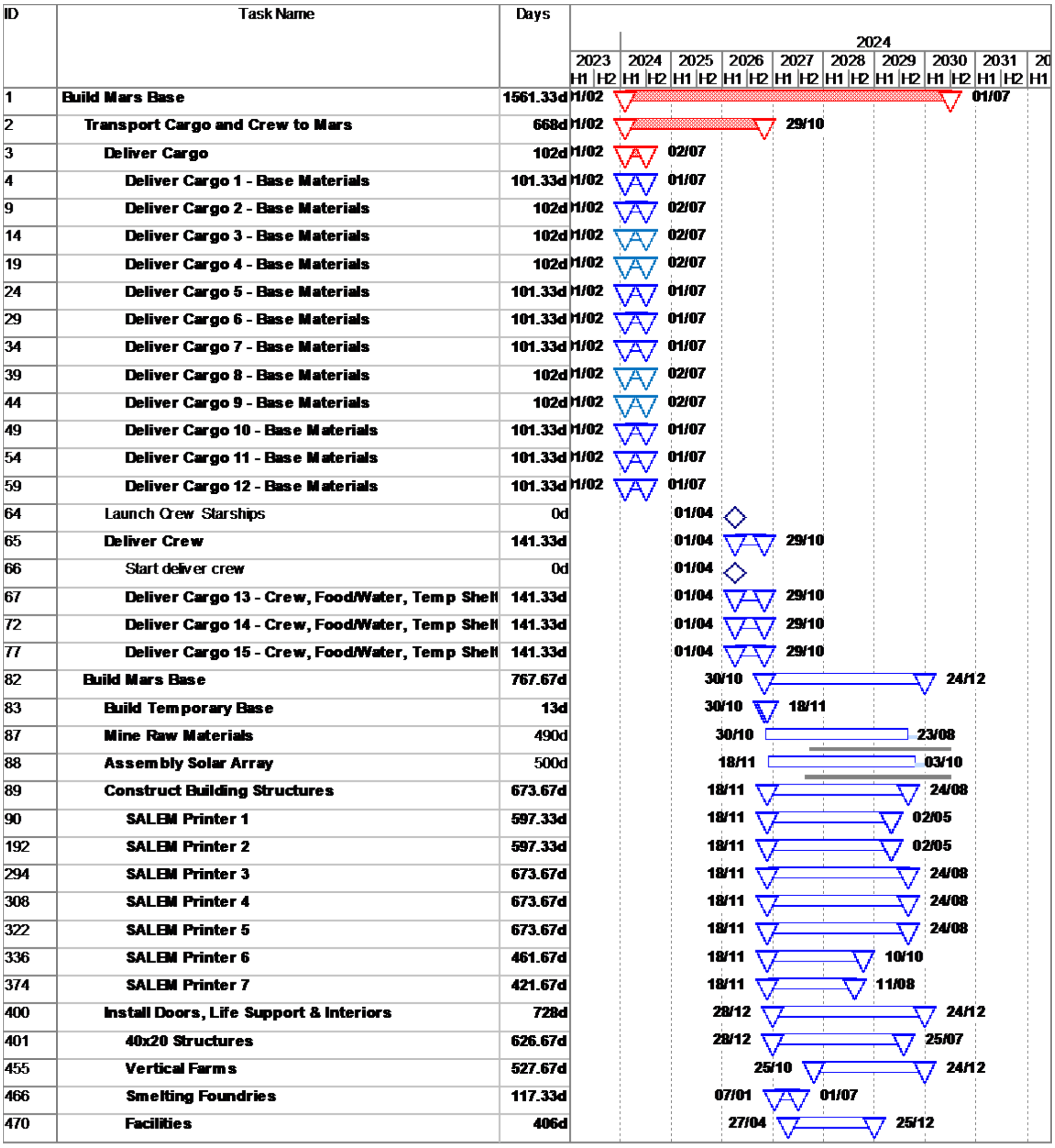
In section *3.1.4 Initial Base and Crew* we calculated that we would need to transport a load of 61,080Kgs just to deliver the crew and a temporary shelter to Mars. Food production on Mars will not immediately be possible so a 1-year supply of food and water will also be required to be sent with the team. Energy production will be paramount to the success of survival and expansion on Mars and a SALEM Printer, mining equipment and cement should be sent with the crew to ensure they are fully equipped to build a permanent presence regardless of whether the craft successfully lands in close proximity to the cargo rockets. If we assume that 10% of allotted base materials are sent at the same time as the crew, we find the total crew launch cargo to be:

Cargo Requirement	Weight (Kg)
Transit Food	7,480
Transit Water	6,000
1 (Mars) Year Food	34,222
1 (Mars) Year Water	27,480
Temporary Shelter	33,863
Transit Vessel	34,000
Entertainment and Comfort	10,000
Personnel & Personal Effects	3,600
600Kwh Solar Array	13,350
100Kwh Battery Grid	8,623
SALEM Printers	9,076.2
Cement	27,360
Mining Equipment	39,091
Transportation	2,000
Tools & Machinery	3,850
Lights & Electronics	13,045
Pressure Lock Doors	1,680
Motors and Spare Electronics	4,000
Total	**278,720.2 Kg**

As each Starship is capable of delivering approx. 100,000 Kgs we will need to send three crewed Starships in the second launch transit cycle, meaning 12 Starship launches in the first launch cycle. The cargo sent by the first 12 Starships should be evenly distributed so that no single spacecraft is mission critical and that if only one craft survives the journey to Mars and lands successfully, the mission can continue at a greatly reduced scope.

3.2.6 Schedule

A hypothetical schedule of work has been created using the assumptions defined in this chapter about base requirements and that the base will be constructed by a crew of 20 people. Lead-times for prints have been approximated based on the size of the structure being printed. A basic 40x20m structure has been assumed to take 24 days to print, whereas complicated, multi-storey structures such as Vertical Farms have been estimated at 160 days total construction time.



Snapshot of Microsoft Project Plan for constructing the Mars Base

For full schedule and resource assessment, see ***Appendix 11 – Mars Base Schedule***

This initial assessment suggests that the barebones structure of the base can be completed in just over 1 Mars year. This is for the basic facilities only. Set up of workshops, decoration and complete wiring and plumbing will take considerably longer than this assessment and it has been assumed that later settlers will perform these activities on arrival. The final 3 Vertical Farms are the current critical path of the schedule. By the third transit cycle of Earth to Mars, the base should be sufficiently developed to support the arrival of up to 1000 new settlers without the need to bring additional food & water.

4.0 Programme Management Plan

4.1.0 Development Programme Structure

4.1.1 Objective & Approach

The primary objective of the SALEM Development Programme is to develop a commercially viable solution for printing large, habitable Structures in hard to reach locations. The Development Programme will utilise a structured validation and verification approach where the Programme is governed by a gated process. Each Gate will represent a significant milestone in the development process, and each consists of a number of programme deliverables being met. The Gates function as decision points for analysing the programmes viability and performance to decide whether to advance to the next level of research and development, stop, or alter course.

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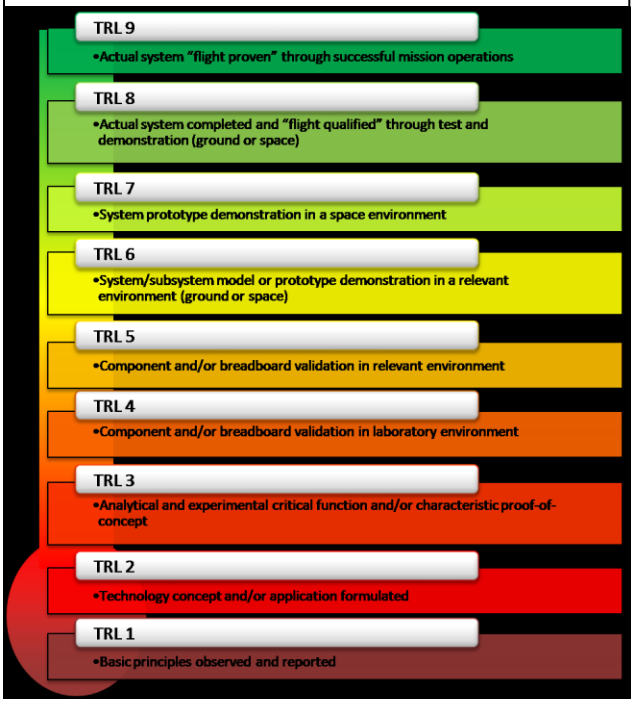
4.1.2 NASA Technology Readiness Level

The NASA Technology Readiness Level system is an effective method of monitoring and guiding the development phases of a technology programme, by breaking the process from conception to production into 9 simple, clearly defined readiness gates. Though this process is aimed specifically at Space and Aerospace applications, with a few minor changes, it can be adapted to reflect any generic C3DP development programme. Below is the broad definition of each Technology Readiness Level for the SALEM Development Programme.

Fig 9: NASA Technology Readiness Level Chart



NASA Technology Readiness Level Chart

SALEM Product Technology Readiness Levels	
TRL 1	Basic Principles Observed and reported.
TRL 2	Technology Concept and/or application formulated.
TRL 3	Analytical and Experimental critical function and/or characteristic proof-of-concept.
TRL 4	Component and/or sub-assembly validation in Laboratory/Simulated environment.
TRL 5	Component and/or sub-assembly validation in relevant environment.
TRL 6	System/Subsystem model or prototype demonstration in a relevant environment.
TRL 7	System Prototype demonstration in a relevant environment.
TRL 8	Actual system completed and "qualified" through test and demonstration.
TRL 9	Actual system "proven" through successful mission and commercial operations.

Individual Experiments will be attributed to each Technology Readiness Level to structure the Development Programme in an efficient manner. Where possible the Programme will aim to demonstrate the technology in an increasing stakes manner such that the fundamental technologies are validated as early on and with minimal funding requirements within TRL1 to 5. Each Technology Readiness Level is further defined into a set of Deliverables required to pass to the next gate. The initial deliverables for the TRL Gates of the SALEM Development Programme are detailed below. For the SALEM 3D Printer TRL1 and TRL2 have already been achieved with the formation of this document. It documents the basic principles of operation and Technology concepts and details several applications fulfilling the requirements for passing TRL 1 & 2.

TRL 1 Deliverables	
1.1	Analysis of Construction 3D Print Market.
1.2	Printer Fundamental functions understood and reported.
1.3	Identify Similar available Technology and primary competitors.
TRL 2 Deliverables	
2.1	Concept CAD Modelled to sub-assembly level.
2.2	Product Analysis Complete and business case defined.
2.3	Initial Product Requirements Drafted.
2.4	Programme Management Plan Drafted.
2.5	Cost/Benefit Analysis Completed.
2.6	Initial Experiments list Generated.
TRL 3 Deliverables	
3.1	A detailed CAD model of the Extruder to component level.
3.2	A detailed CAD model of the Hoist to component level.
3.3	CAD Stress analysis completed on the full printer model to determine the key technology risks associated with the printer and to develop the validation and verification strategy to mitigate these risks.
3.4	A comprehensive Experiments list that details a strategy for fulfilling all product/design requirements including any identified technology risks.
3.5	A proof-of-concept of the suspended Extruder Travel concept. (Simulated or Scaled)
3.6	Proof-of-concept of calibration method for Extruder, Support Structure and Hoists.

TRL 4 Deliverables	
4.1	Design optimised for performance and function for all applications.
4.2	Validation of the Variable Extruder Nozzle concept.
4.3	Component Procurement analysis complete.
4.4	Print software developed to execute a full suite of Extruder movements across a 3-dimensional plane (x,y,z)
4.5	Tooling concept devised and initial design complete.
4.6	Assembly Method generated and validated.
TRL 5 Deliverables	
5.1	Experimental validation of the Extruder Nozzle design across a range of climates and operation variables.
5.2	Experimental Validation of the Hoist tracking system (Scaled or Full)
5.3	Experiments matured and scope locked down. Information on exact parameters to be tested and sensors agreed. All experiments past this point require Scope Change Management.
5.4	All sub-system Rig test drawings and experimental hardware ready for manufacture.
5.5	Print Software optimised and expanded to include secondary tracking and full scope of advanced print features.
5.6	Detailed tooling designs completed and validated in a simulated or scaled environment.
TRL 6 Deliverables	
6.1	Rig Tests completed on Extruder operability. (Scaled or Full)
6.2	Rig Tests completed on Support Structure operability. (Scaled or Full)
6.3	Rig Tests completed on Hoist operability. (Scaled or Full)
6.4	Rig Tests Completed on Cement Delivery System. (Scaled or Full)
6.5	Print Software Validated in a non-simulated environment (Scaled or Full).
6.6	Manufacture requested for prototype SALEM Printer and standard toolset.
TRL 7 Deliverables	
7.1	One or more SALEM printers assembled and tested in a control site. (Scaled or Full)
7.2	Small scale (Less than 10m^2) Print completed.
7.3	Detailed 2-person assembly tooling designs completed and ready for manufacture.
7.4	Experiments Fully defined and final instrumentation hardware ordered.
7.5	Design Finalised for Development Projects.
7.6	Manufacture requested for SALEM Development Programme.

TRL 8 Deliverables	
8.1	All Printer Operability and Safety Testing Complete.
8.2	First Multi-storey Structure printed.
8.3	All Printer Software features verified and validated.
8.4	New Product Introduction Plan finalised.
8.5	2-Person Assembly Tooling Design locked down and manufacture requested.
8.6	Production Assembly documentation finalised.
TRL 9 Deliverables	
9.1	All Experiments in the SALEM Development Programme completed.
9.2	2-Person Assembly Tooling Validated and Verified.
9.3	Pre-production complete.
9.4	Regulatory Compliance Achieved.
9.5	First Structures Printed on Mars.
9.6	All SALEM Printer key Success Criteria met or deferred.

4.1.3 Development Phases (DP#)

In conjunction with the TRL approach described above, the intention is to split the Development Programme into four general phases of increasing complexity and investment requirements; each Phase will more than likely overlap with the next to reduce the total Development time. The four Phases are:

4.1.3 DP1 - Scaled Print

The first level of development entails designing, building and testing the SALEM Printer at a scaled (desktop) level. The aim of this Development Phase is to provide a proof of concept for the printing method and to aid in development of the Printer software package and is not intended to provide much validation of exact design details, material properties, advanced functions or secondary sensors.

This development phase should be the lowest cost of all 4 phases by reusing, where possible, the initial design concept and procuring off the shelf parts for as much of the functionality as possible. This phase does not require any specific experimentation on the Extruder or Support Structure, so these elements can be simplified or substituted and cheap fast make solutions can be used to procure parts. The Support Structure, Housings and Extruder for instance, could all be 3D Printed in ABS or PLA.

TRL3 as defined above can be achieved by completing this initial phase of simple Scaled Testing and will also aid in the completion of TRL4.4 – "Print software developed to execute a full suite of Extruder movements across a 3 dimensional plane (X,Y,Z)"

4.1.3 DP2 - Rig Assemblies

The aim of the Rig assemblies Phase is to validate the individual elements of the SALEM printer through Rig tests and other isolated representations with the key goal of proving basic operability in normal working/optimal conditions. The Rig tests will also provide the programme with an opportunity to test more advanced software functions that can't be ran on the Scaled Printer.

Rig assemblies can be completed using Part designs that have not been optimised and manufacture should be time-driven rather than quality-driven as the Experiments enacted at this phase are aimed at basic functionality, rather than performance.

It should be possible to achieve all the deliverables up to and including TRL6 by completing the Rig Assembly Phase (DP2).

4.1.3 DP3 - SALEM Earth Print

The SALEM Earth Print Phase aims to validate and verify the Printer under normal working conditions but will not necessarily prove out the technologies/design features that will allow the printer to be operated on Mars or other extreme environments. The vast majority of Operability, Performance and Safety testing will be completed at this phase, barring only advanced features such as heated Cement feed system and Foundation printing as well as extreme weather testing.

As the working environment on Earth is so strikingly different to that of Mars, it may be more logical to break the SALEM Printer into two distinct products; one for applications on Earth, the other for applications in space.

This Development Phase should enable up to and including TRL8 to be passed.

4.1.3 DP4 - SALEM Mars Print

The SALEM Mars Print Phase is intended as the final phase of the SALEM Development Programme and will be the hardest and most expensive Development Phase to pass. This is because this phase requires tests to be completed on the SALEM printer in a relevant environment. This effectively means sending at least one SALEM Printer to Mars and successfully printing Habitable Structures with it.

Before sending the Printer to Mars for the final testing, several Experiments will be performed on Earth to test the Printers functionality under extreme conditions that are as Close to those expected on Mars and beyond as possible. These include extreme cold, vacuum testing and various Mars-comparable aggregates as well as Experiments with the 2-person assembly tooling to prove that the Mars astronauts will be able to assemble the Printer on arrival.

This Development Phase should meet all deliverables left to achieve Technology Readiness Level 9.

4.2.0 Experiments

4.2.1 Approach

The below experiments list is a first pass and does not represent all tests that should be completed. This list is intended as a starting point for experimental definition and will require several updates as the Product design matures and operational requirements are better understood.

The Experiments have been aligned to the Development Phases described in the previous chapter. DP1 ensures that the basic concept is proven via a single desktop prototype, DP2 deals with the Experiments that can be performed on Rig tests and is broken into 5 elements; Extruder Rigs, Hoist Rigs, Structure Rigs, Control Deck Tests and Cement Delivery System Rigs.

DP3 Experiments are focused on the function and performance of the SALEM Printer assembly under conditions that could be experienced on Earth and the final phase, DP4, extends this testing to conditions experienced on Mars.

By TRL5 all experiments should be raised and agreed and a Change Management process should be put in place to manage any changes. All rig tests should be completed by TRL6 which could potentially necessitate additional experiments to mitigate or further investigate any findings. By TRL7 the entire system should have undergone relevant testing (Scaled or Full) and all experiments should therefore be fully defined.

4.2.2 Experiment Types

There are several different types of experiments that need to be performed on the SALEM Printer to ensure Safety, Performance and Function are validated and verified. Below are the various types of Experiments utilised at different Developmental Phases of the SALEM Development Programme.

4.2.2 Functionality

Operability testing

Operability testing will cover the full Manoeuvre range of the printer from basic straight-line travel to complex print paths. This will help validate the basic printer function and evaluate potential print quality, as well as shed light on the factors which may reduce print quality.

Heavy Operability test

This is as Operability testing but with over-weight components and sub-assemblies. This will help evaluate how the print quality will be affected by the Hoist motors etc aging and losing torque capacity.

Max Travel Speed

Several manoeuvres will be completed at various travel speeds to determine the Max operation speed that meets tolerance requirements and will help validate safety procedures aimed at preventing print failure when operated overspeed.

Max Flow Rate

Cement is flowed through the system at variable speeds to assess reactivity at different flow rates and nozzle operability. These Tests should help determine the optimal print speed under normal use.

Grit Test

Several different cement mixtures will be extruded at different consistencies progressively getting courser. This is to assess the boundaries for useable aggregates and validate repeatable use with the intended cement mixture.

Nozzle Control

This experiment will validate the functionality of the variable nozzle by first testing operability without cement extrusion and then with a flow of cement to demonstrate control of extrusion thickness and diameter.

Calibration

Calibration tests will be aimed at proving and optimising printer calibration procedures to ensure printer set-up is as simple and repeatable as possible.

Assembly

These tests will determine if the assumptions about assembling the Printer are correct and feasible. The primary goal of the assembly tests is to validate that the printer can be erected with just two people without overhead cranage.

4.2.2 Integrity

Maturity

To determine the printer reusability, it is necessary to repeat several actions hundreds or potentially thousands of times. These include basic manoeuvres, assembly and disassembly, motor actuation and a representative print schedule.

Structural Integrity

A number of stress and strain experiments to evaluate the structural integrity of the printer under normal and sub-optimal operation. This testing would likely be 'Piggy back' experiments; i.e testing that can be done passively during other experiments by applying additional instrumentation.

Weather

In order to validate the printers' capability to print in extreme environments a suite of Weather oriented experiments should be completed. These include:

- **Cold Start:** The Printer assembly will be cooled down to -200 Degrees Fahrenheit and a print procedure is run to determine printer operability in extreme cold.
- **Hot start:** The Printer assembly will be heated up to 120 Degrees Fahrenheit and a print procedure is run to determine printer operability in extreme heat.
- **Crosswind Test:** Using large fans, several print procedures will be run at different simulated wind speeds to assess how the print quality is affected by strong winds. At certain wind speeds the printer should perform an automatic safety procedure to minimise the risk of structural collapse or loss of Extruder.
- **Rain and Hail ingestion:** Heavy rain and hail will be simulated during a print procedure to assess the effect on print quality and printer operation.
- **Low atmosphere:** Printer will be run at different atmospheric pressures to determine how the print quality and integrity is affected by the lack of a thick atmosphere.
- **Simulated earthquake:** The printer structure Foot assemblies will be fitted to rigs that allow sudden movement and undulation to simulate an earthquake. This is to assess how effective the printer is at identifying an earthquake, pausing print and then returning to the correct print position once the earthquake has subsided. This test will also assess the printer safety and integrity during an earthquake.
- **Ground Subsidence:** This test will simulate the loss of one or more Structure Legs to demonstrate safety procedures during a ground subsidence scenario.
- **Ice Ingestion:** In the event of a failure of the heating system between the Cement Delivery System and the Extruder, it may come to pass that Ice or other frozen particulates are passed through the

Printer. If this occurs the printer must be able to recognise the problem, pause the print and notify the operator of the problem.

- **Temperature Stress:** Because the atmosphere is so thin on Mars it is not unusual for the Temperature to swing wildly in a short space of time. It is therefore necessary that the Printer does not warp or excessively wear due to this.
- **Radiation Ingestion:** On Mars, the SALEM Printer will be subjected to much higher levels of radiation from the sun. It is important to understand what affects this has long term on the printer and print integrity.

4.2.2 Safety

Simulated Failure Tests

Various tests simulating component/ sub-assembly failure to ensure the design has relevant redundancy to protect the print and human life if/when an incident occurs.

Overspeed Tests

This series of tests push the Printer above and beyond calculated safe operating parameters incrementally until failure occurs to ensure that if a malfunction should occur that removes these boundaries that the Printer will fail in a safe manner.

Safety Feature Tests

This will test a suite of built in features the printer has to protect the print and human life if a malfunction should occur.

4.2.2 Cement Structures

Profiles

In these tests, various printed structures will be generated. These include a linear wall; a cylindrical structure and cross axis profiles will be generated to prove basic functionality of the SALEM Printer as an integrated cement extrusion technology.

Single Floor Structure

This test will seek to print a single floor building to prove that useful structures can be constructed using the SALEM Printer and to test the real-world speed at which the printer can complete a structure.

Multi-level Structure

These experiments will build on the single floor structure tests to prove that multi-floor structures can feasibly be built using the SALEM Printer. This will also potentially include printing a prototype version of a Vertical Farm.

Tolerance Tests

Several experiments will be completed during the construction of profiles and structures to determine the limits and tolerances that the SALEM Printer can achieve in terms of print quality.

Run Off Tests

In these experiments the printer will be paused mid print and emergency stops will be completed to determine how much cement run off occurs.

Disruption Testing

The Printer will also be forcefully disrupted during print to assess the printer's capability to protect the printed structure from damage or malformation in conditions of extreme disruption.

4.2.3 Development Phase 1 – Desktop Tests

The core purpose of the Desktop SALEM Prototype is to provide a practical platform for the programming team to test early versions of the print software. The desktop test vehicles are intended to be fluid and amended/upgraded as the technology concept evolves. To allow for cheap, continuous upgrades to the desktop test printer, it will be predominantly manufactured through 3D printing on site. The SALEM Desktop printer will not feature advanced functions such as automatic temperature control or secondary sensory features. The Desktop printer can be considered a rig assembly as it will also be unlikely to feature a working cement system or Extruder. Other desktop prototypes may also be 3D printed and mocked up in this development phase to provide proof of concept of other SALEM technologies such as the variable Extruder Nozzle.

The current planned experiments for the SALEM Desktop prototype are largely based around proving the concept of moving the Extruder point to point, in a controlled manner, along a complex trajectory via hoisted suspension. The Desktop Printer also offers the opportunity to prove that it is possible to operate the printer accurately in an irregular print envelope as well as lay the foundation for the calibration sequence.

№	Experiment Name	Description	Vehicle
1	Basic Manoeuvres - XY Travel	Basic Linear 2D movements	Desktop
2	Basic Manoeuvres - XYZ Travel	Basic Linear 3D Movements	Desktop
3	Basic Manoeuvres - Traverse	Basic Traversal Movements in shapes	Desktop
4	Extruder Nozzle Function - Concept	Proof of concept of the extruder nozzle function	Desktop
5	Hoist Travel - Concept	Proof of concept of the hoist travel and suspension functions	Desktop
6	Calibrate Hoists - Concept	Proof of concept of the hoist relative location calibration process	Desktop
7	Calibrate Extruder - Concept	Proof of concept of the Extruder Calibration Process	Desktop
8	Calibrate Ground - Concept	Proof of concept of the Ground location and print envelope Calibration process	Desktop

For full experiment details please refer to ***Appendix 8 – Experiments List***

4.2.4 Development Phase 2 – Rig Tests

4.2.4 Extruder Experiments

The Extruder rig tests are focused on determining the basic functionality of the module and providing the design and stress teams data on the strengths and weaknesses of the component level design to optimise for the integrated SALEM printer design. The Extruder rig tests will also provide some early indication of the feasibility of printing on Mars by enacting some initial radiation and cold testing.

No	Experiment Name	Description	Vehicle
9	Extruder - Max Flow Rate	Flow rate increased in stages up to calculated Max Flow Rate	ER01.1
10	Extruder - Grit Ingestion	Various course Aggregates are processed through the Extruder of increasing coarseness until failure occurs	ER02.2
11	Extruder - Nozzle Control	Cement is extruded at varying diameters and dynamically changed during print	ER01.1
12	Extruder - Nozzle Strain	Nozzle is opened in stages and cement pressure is increased to Max Cement Flow Pressure	ER02.1
13	Extruder - Cold Start	Extruder is frozen to -40 degrees C and initiated	ER02.1
14	Extruder - Radiation Ingestion	The extruder is exposed to large, repeat doses of electromagnetic energy for many cycles then tested for functionality	ER02.3
15	Extruder - Suspension	Suspend the extruder and move dynamically	ER01.1
16	Extruder - Control Rod Failure	Run the Extruder under normal operation with a damaged or missing Control Rod	ER03.1
17	Extruder - Actuator Failure	Run the Extruder under normal operation with a damaged or missing Actuator	ER03.1
18	Extruder - Nozzle Plate Failure	Run the Extruder under normal operation with a damaged or missing Nozzle Plate(s)	ER03.2
19	Extruder - Pump Screw Failure	Run the Extruder under normal operation with a damaged or missing Pump Screw	ER03.3
20	Extruder - Cement Hose Failure	Run the Extruder under normal operation with a damaged Cement Hose and/or fixture	ER03.3
21	Extruder - Disturbance	Extruder is pushed/shook at varying intensities during operation	ER01.1
22	Extruder - Ice Ingestion	Chunks of Ice are fed into the Extruder during operation	ER02.1
23	Extruder - Overspeed	Extruder is Operated above calculated safe limit in increments until failure occurs	ER01.2
24	Extruder - Heat Stress	Extruder is repeatedly frozen and heated during print over many cycles	ER02.1
25	Extruder - Calibration	Extruder is calibrated to recognise ground height	ER01.1

For full experiment details please refer to ***Appendix 8 – Experiments List***

4.2.4 Hoist Experiments

The Hoist rigs will provide a similar array of experiment opportunities as the Extruder rigs. This includes basic functionality tests to check assumptions about operation are correct and also a suite of experiments aimed at pinpointing the boundaries of operability.

No	Experiment Name	Description	Vehicle
26	Hoist - Max Cable Travel Speed	Spool Motor operated in increments up to calculated Max safe Travel Speed.	HR01.1
27	Hoist - Cable Overspeed	Spool Motor Operated above calculated limit in increments until failure occurs	HR01.1
28	Hoist - Max Track Travel	Track motor operated in increments up to calculated Max safe Travel Speed.	HR01.2
29	Hoist - Track Travel Overspeed	Track Motor Operated above calculated safe limit in increments until failure occurs	HR01.2
30	Hoist - Max Cable Lift Weight	Cables are torqued in increments to calculated Max safe operating force	HR01.3
31	Hoist - Cable Overstrain	Cables are torqued in increments above Max motor capability until failure occurs	HR01.3
32	Hoist - Max Track Lift Weight	Track Motors are operated in torque increments to calculated Max safe operating force	HR01.2
33	Hoist - Cable Failure	Run the Hoist under normal operation with a damaged Cable	HR03.1
34	Hoist - Track Gear Failure	Run the Hoist under normal operation with a damaged or missing Track Gear	HR03.2
35	Hoist - Track Motor Failure	Run the Hoist under normal operation with a damaged or missing Track Motor	HR03.3
36	Hoist - Cable Control	Cable extension/retraction procedures at varying torques, speeds and increment lengths	HR01.1
37	Hoist - Cable Extension	Measure the length of the cable at different extensions to check calculated length is correct	HR01.1
38	Hoist - Cable Torsion	Operate Hoist with the Cable twisted at incremental angles	HR02.1
39	Hoist - Cold Start	Hoist is frozen to -40 degrees C and initiated	HR02.1
40	Hoist - Heat Stress	Hoist is repeatedly frozen and heated during print over many cycles	HR02.1
41	Hoist - Disturbance	Hoist is pushed/shook at varying intensities during operation	HR01.1
42	Hoist - Radiation Ingestion	The Hoist is exposed to large, repeat doses of electromagnetic energy for many cycles then tested for functionality	HR02.2
43	Hoist - Sand Ingestion	Hoist is operated in a simulated heavy sandstorm	HR02.3
44	Hoist - Rain and Hail Ingestion	Hoist is operated in a simulated heavy rain and hailstorm	HR02.4
45	Hoist - Calibration	Hoist is calibrated to recognise min/max cable extension lengths and elevation.	HR01.1

For full experiment details please refer to ***Appendix 8 – Experiments List***

4.2.4 Support Structure Experiments

Outside of the operability experiments that are common to all rig tests, the Support Structure rigs will also provide feedback on the feasibility of printing extremely large structures by determining the rate of grid deflection at extension lengths required to print a structure such as the Vertical Farm described in chapter 3.1.0.

No	Experiment Name	Description	Vehicle
46	Support - Grid Deflection	A force above calculated Max operating load is applied to the Support Leg at different heights and deflection is measured.	SR01.1
47	Support - Overstrain	Force is applied to the Support Leg at different heights until failure	SR01.1
48	Support - Calibration	Support Leg is calibrated to 90 degrees manually and automatically and checked for levelling.	SR01.1
49	Support - Heat Stress	Support is repeatedly frozen and heated during print over many cycles	SR02.1
50	Support - Radiation Ingestion	The Support is exposed to large, repeat doses of electromagnetic energy for many cycles then tested for functionality	SR02.2
51	Support - Track Integrity	A hoist is repeatedly lifted and lowered on the Support Leg Track	SR01.1
52	Support - Corrosion Resistance	Support is sprayed with corrosive substances repeatedly and used	SR01.2
53	Support - Foot Sole Failure	Apply varying loads to the Support Leg with a damaged Foot Sole Piece	SR03.1
54	Support - Pivot Failure	Apply varying loads to the Support Leg with a damaged Pivot/ Pivot Housing	SR03.2
55	Support - Grid Piece Failure	Apply varying loads to the Support Leg with a damaged Grid Piece	SR03.3
56	Support - Ground Screw Failure	Apply varying loads to the Support Leg with a damaged Ground Screw	SR03.4
57	Support - Support Rod Failure	Apply varying loads to the Support Leg with a damaged or missing Support Rod	SR03.5
58	Support - Ground Water Ingestion	Saturate the Support Leg foundation with water in various substrates and apply force	SR01.2

For full experiment details please refer to ***Appendix 8 – Experiments List***

4.2.4 Controls Deck Experiments

As the Control Deck will typically be utilised in less harsh environments than the other SALEM Printer modules, there is not as much need to collect initial rig data on the Control Deck performance. Control Deck experimentation will be far more crucial as an integrated element of the SALEM Printer than as an individual module. That said, the Control Deck rigs offer a chance to subject the module to some extreme environments and prove basic functionality.

No	Experiment Name	Description	Vehicle
76	Controls - Heat Stress	Control Deck is repeatedly frozen and heated during operation over many cycles	COR02.1
77	Controls - Cold Start	Control Deck is frozen to -40 degrees C and initiated	COR02.1
78	Controls - Functionality	Basic run through of all Control Deck functions	COR01.1
79	Controls - Calibration	Control Deck is calibrated to recognise all System Datums	COR01.1
80	Controls - Manual/Emergency Pause	An emergency stop is initiated	COR01.1
81	Controls - Radiation Ingestion	The Control Deck is exposed to large, repeat doses of electromagnetic energy for many cycles then tested for functionality	COR02.2
82	Controls - Surge Control	The Control Deck is subjected to an electrical surge	COR01.2

For full experiment details please refer to ***Appendix 8 – Experiments List***

4.2.4 Cement Delivery System Experiments

The Cement Delivery System Rigs are important for providing initial data on cement flow and attributes when in extreme and changing environments. The Cement System will be one of the most vulnerable modules to failure because of the need to maintain high pressure within the system.

No	Experiment Name	Description	Vehicle
59	Cement System - Max Flow Rate	Run the Cement Delivery System up to Max Calculated Cement Flow Rate.	CR01.1
60	Cement System - Overflow	Run the Cement Delivery System beyond Max Calculated Cement Flow Rate in increments until failure occurs	CR01.1
61	Cement System - Git Ingestion	Various course Aggregates are processed through the Cement Delivery System of increasing coarseness until failure occurs	CR02.1
62	Cement System - Flow Control	Cement is pumped at varying Flow Rates and dynamically changed during print	CR01.1
63	Cement System - Max Absolute Pressure	Cement System is pumped to Max safe calculated system pressure in increments	CR01.2
64	Cement System - Over Pressure	Cement System is pumped above and beyond Max safe calculated system pressure in increments until failure occurs	CR01.2
65	Cement System - Ice Ingestion	Chunks of Ice are fed into the Cement Delivery System during operation	CR02.1
66	Cement System - Cold Start	Cement Delivery System is frozen to -120 degrees C and initiated	CR02.1
67	Cement System - Heat Stress	Cement Delivery System is repeatedly frozen and heated during print over many cycles	CR02.1
68	Cement System - Vacuum Performance	Cement System is run in a Vacuum similar to that on Mars	CR01.2
69	Cement System - Radiation Ingestion	The Support is exposed to large, repeat doses of electromagnetic energy for many cycles then tested for functionality	CR02.2
70	Cement System - Disturbance	Cement System is pushed/shook at varying intensities during operation	CR01.1
71	Cement System - Calibration	Cement System flow rate is calibrated	CR01.1
72	Cement System - Cement Hose Failure	Apply varying loads to the System with a damaged Cement Hose	CR03.1
73	Cement System - Pump Failure	Apply varying loads to the System with a damaged Cement Pump/Motor	CR03.2
74	Cement System - Tank Failure	Apply varying loads to the System with a damaged Cement Tank	CR03.3
75	Cement System - Heating System Failure	Apply varying loads to the System with a damaged Heating System	CR03.4

For full experiment details please refer to ***Appendix 8 – Experiments List***

4.2.5 Development Phase 3 – Earth SALEM Tests

The experiments at development phase 3 are intended to bring the SALEM Printer to a production ready state for all Earth-bound applications. At DP3 experiments will be completed on the full printer assembly and will include a range of tests that exert conditions far harsher than what can be expected on Earth. This includes freezing the printer down to potentially as low as -120 degrees Celsius as well as a test at 0.5% atmospheric pressure. These tests will simulate conditions that can be expected on Mars and will provide early evidence that the SALEM Printer will be capable of functioning on Mars.

This phase will also demonstrate advanced features such as laying foundation layers and secondary sensory functions and will also demonstrate the 2-person assembly method. At this stage several structural prints will be completed to demonstrate the feasibility and potential profitability of the Printer as an alternative to traditional construction methods and should also provide a proof of concept for C3D Printed Vertical Farms.

No	Experiment Name	Description	Vehicle
83	EARTH SALEM - Operability	Operate the printer under normal conditions across the full range of usage	EA01.1
84	EARTH SALEM - Heavy Operability	Operate the printer across a full range of usage with additional weight on the Extruder and Hoists	EA01.3
85	EARTH SALEM - Max Travel Speed	Run the SALEM Printer up to Max Calculated travel speed in increments	EA01.2
86	EARTH SALEM - Overspeed	Run the SALEM Printer over MAX Calculated travel speed in increments until failure occurs	EA01.2
87	EARTH SALEM - Structural Integrity	Measure stress and strain of all key components in normal operating conditions	EA01.1
88	EARTH SALEM - Maturity Cycles	Repeated operation under normal conditions for many cycles	EA04.1
89	EARTH SALEM - Cold Start	Printer is frozen to -120 degrees C and initiated	EA02.1
90	EARTH SALEM - Hot Start	Printer is Heated to 120 degrees C and initiated	EA02.1
91	EARTH SALEM - Crosswind	Printer is operated under various incremental levels of crosswind	EA02.3
92	EARTH SALEM - Rain and Hail ingestion	Printer is operated in incrementally intense levels of Rain and Hail	EA02.2
93	EARTH SALEM - Vacuum performance	Printer is operated in a Vacuum	EA01.2
94	EARTH SALEM - Simulated Earth Quake	Printer is subjected to earthquake like tremors/shaking during operation	EA04.2
95	EARTH SALEM - Disturbance	Printer is subjected to sudden shaking at various intensities during operation	EA01.1
96	EARTH SALEM - Lightning	Printer is subjected to a simulated lightning strike during operation	EA05.1
97	EARTH SALEM - Ground Subsidence	The ground below at least one Support Leg is subsided during operation	EA05.2

98	EARTH SALEM - Calibration	Printer final calibration procedure	EA01.1
99	EARTH SALEM - Cable Failure	Apply varying loads to the System with a damaged or missing Cable	EA03.1
100	EARTH SALEM - Hoist Failure	Apply varying loads to the System with a damaged or missing Hoist	EA03.2
101	EARTH SALEM - Extruder Failure	Apply varying loads to the System with a damaged or missing Extruder	EA03.3
102	EARTH SALEM - Support Leg Failure	Apply varying loads to the System with a damaged or missing Support Leg	EA03.4
103	EARTH SALEM - Cement Delivery Failure	Apply varying loads to the System with a damaged or missing Cement Delivery System	EA03.3
104	EARTH SALEM - Basic Manoeuvres	Basic Manoeuvre operation	EA01.1
105	EARTH SALEM - Advanced Manoeuvres	Advanced Manoeuvre operation	EA01.1
106	EARTH SALEM - Pause and Print	Emergency Print Pause operation	EA01.1
107	EARTH SALEM - Performance	Printer is run at max tolerance and speed and various complex prints are completed	EA01.1
108	EARTH SALEM - Single Storey Print	A full single storey structure is printed by the SALEM Printer	EA01.1
109	EARTH SALEM - Multi-storey Print	A full Multi storey structure is printed by the SALEM Printer	EA04.1
110	EARTH SALEM - Print optimisation	Print time and quality are optimised for maximum performance	EA05.1
111	EARTH SALEM - Advanced Geometry Print	Complex and intricate structures are printed	EA05.1
112	EARTH SALEM - Wet Print	A print is completed during heavy rainfall (simulated)	EA05.1
113	EARTH SALEM - Max Print Envelope	Printer is configured for Max calculated Print Envelope and operated	EA05.3
114	EARTH SALEM - Vertical Farm Print	A full Vertical Farm is printed	EA06.1
115	EARTH SALEM – 2-man Assembly	Printer is assembled using the 2-person (no overhead crane) method	EA02.3
116	EARTH SALEM - Mid print Maintenance	Printer is paused during operation and various maintenance and part replacement tasks are performed	EA02.3

For full experiment details please refer to ***Appendix 8 – Experiments List***

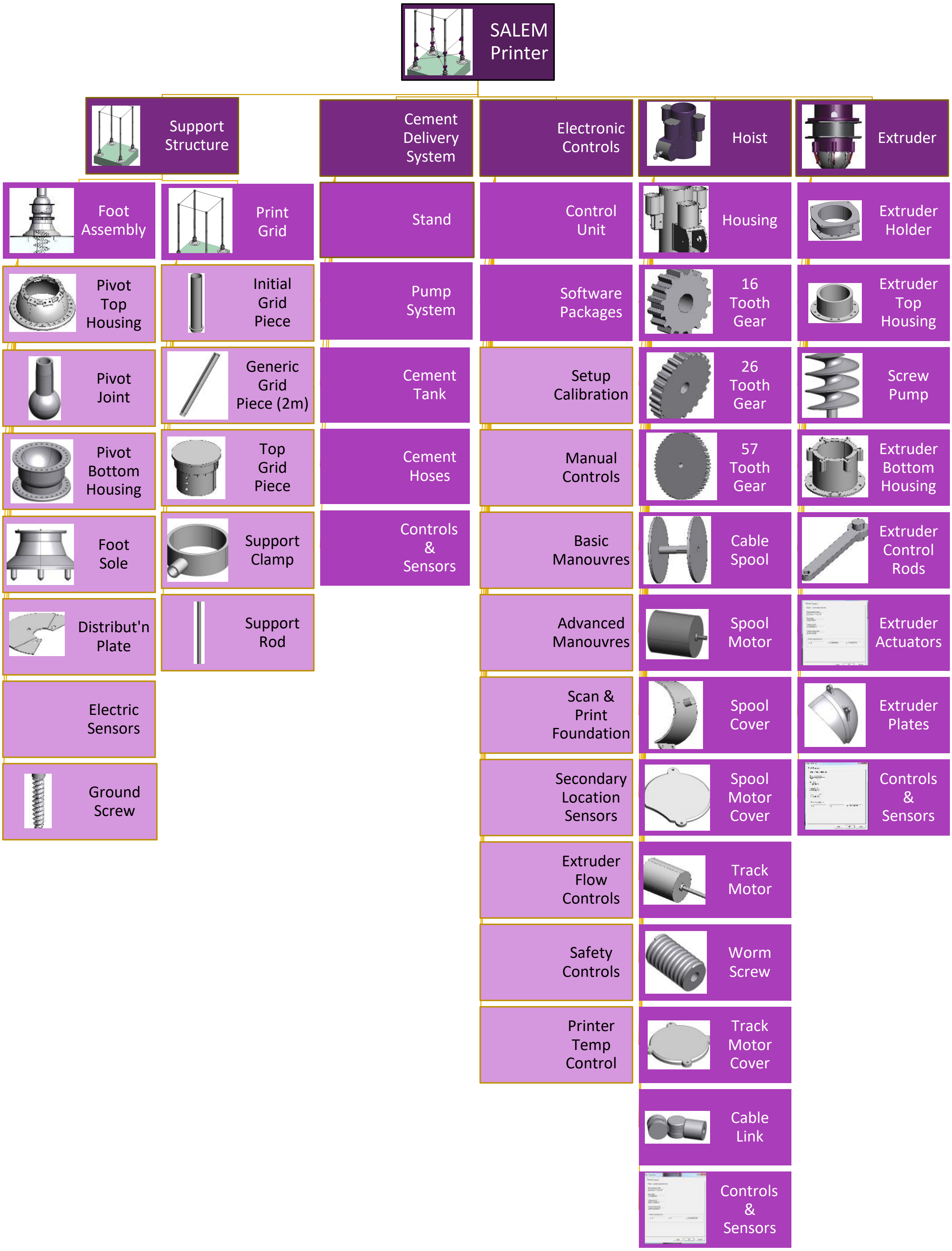
4.2.6 Development Phase 4 – Mars SALEM Tests

Development Phase 4's purpose is to verify that the printer is capable of functioning on Mars and will establish the first permanent human structures on the planet, which may eventually become part of an established colony. As most of the operability and performance testing will have already been completed in DP3, the number of experiments to be completed at this stage are minimal. The majority of testing at this stage will be in the form of complete structures. If successful, this mission will also provide infrastructure for humans to utilise in future Mars missions.

No	Experiment Name	Description	Vehicle
117	MARS SALEM - Operability	Operate the printer under normal Mars conditions across the full range of usage	MA01.1
118	MARS SALEM - Performance	Printer is ran at max tolerance and speed and various complex prints are completed	MA01.1
119	MARS SALEM - Single Storey Print	A full single storey structure is printed by the SALEM Printer	MA01.1
120	MARS SALEM - Multi-storey Print	A full Multi storey structure is printed by the SALEM Printer	MA01.1
121	MARS SALEM - Vertical Farm Print	A full Vertical Farm is printed	MA02.1
122	MARS SALEM - Natural Aggregate	Mars sourced Aggregate is processed and used to print with	MA01.1

For full experiment details please refer to ***Appendix 8 – Experiments List***

4.3.0 Product Breakdown Structure



4.4.0 Work Breakdown Structure

Now the product is defined we can break it down into groups of tasks to generate a Work Breakdown Structure (WBS). Each item in the Product Breakdown Structure (PBS) will need requirements and experiments defined, designs generated, and parts manufactured, assembled and tested to some degree. If we align the work breakdown into Development Phases as described in section 4.3.4, we can express the work to be done in terms that can easily be quantified for each gate.

4.4.1 Development Phase 1 – Desktop Prototyping

The desktop prototyping phase (DP1) is aimed at providing a sandbox opportunity for software, assembly, development and design engineers to test the basic concepts of the SALEM Printer. As such this phase should be treated with flexibility with the work structure to allow for late experiment requests.

The SALEM desktop printer will be a stripped down, crude version of the final printer and will not feature a Cement Delivery System, so will not be fully functional. This will represent the earliest stage of SALEM Printer design. The concept design will be modified to interface with small scale motors and electronics and individual SALEM components or subassemblies may be modified, upgraded or replaced as new challenges or opportunities present themselves.

To achieve TRL3, this development phase must demonstrate basic Extruder manoeuvres and calibration of the print envelope. The work breakdown structure for DP1 for the activities to achieve TRL3 can be seen to the right.

Task Name
DEVELOP THE SCALED PROTOTYPE PRINTER
DEVELOP SCALED PRINTER REQUIREMENTS
START PROJECT REQUIREMENTS
DEFINE OBJECTIVES AND SUCCESS CRITERIA
DEFINE REQUIREMENTS
DEVELOP SCALED PRINTER EXPERIMENTS
DESIGN SCALED 3D PRINTER
DESIGN PRINTER STRUCTURE
DESIGN VARIABLE HOIST
DESIGN EXTRUDER
DESIGN ELECTRICAL CONTROLS SYSTEM
DESIGN COMPLETE
PROCURE SCALED PRINTER COMPONENTS
PROCURE PRINTER STRUCTURE COMPONENTS
PROCURE VARIABLE HOIST COMPONENTS
PROCURE EXTRUDER COMPONENTS
PROCURE ELECTRICAL CONTROLS COMPONENTS
COMPONENTS AVAILABLE FOR BUILD
ASSEMBLE SCALED SALEM PRINTER
START PRINTER ASSEMBLY PROCESS
GENERATE INSTRUCTIONS TO BUILD
ASSEMBLE SCALED PRINTER
MODULAR BUILD
BUILD VARIABLE HOISTS
KIT VARIABLE HOISTS
VARIABLE HOIST 1
VARIABLE HOIST 2
VARIABLE HOIST 3
VARIABLE HOIST 4
VARIABLE HOIST 5
VARIABLE HOIST 6
VARIABLE HOIST 7
VARIABLE HOIST 8
VARIABLE HOISTS AVAILABLE FOR FINAL ASSEMBLY
BUILD EXTRUDER
NON-MODULAR BUILD
PERFORM SCALED PRINTER TESTS

TRL 3	Analytical and Experimental critical function and/or characteristic proof-of-concept.

4.4.2 Development Phase 2 – Rig Development

The Rig development phase (DP2) will need several individual rig test vehicles that are based on the requirements of the validation and verification team for tests.

The current DP2 experiments list necessitates fourteen separate rig test vehicles; three Hoists, three Extruders, three Support Structures (part or whole), three Cement Delivery Systems and two Control Decks. Each of these vehicles have various amounts of rework for further testing and all require parts to be procured. As with DP1, the specific requirements for the SALEM Rig project will need defining and the experiments will need to be updated as part of the work schedule.

The next level of design will be completed at this development phase and will be a complete redesign of the SALEM printer down to component level. The design at this level will be functional but not high performance or aesthetically pleasing and is intended to prove basic operation only.

To achieve TRL6 within the Rig phase we must have captured all work to validate that each of the modules of the SALEM Printer performs the general function claimed in this proposal.

TRL 4	Component and/or sub-assembly validation in Laboratory/Simulated environment.
TRL 5	Component and/or sub-assembly validation in relevant environment.
TRL 6	System/Subsystem model or prototype demonstration in a relevant environment.

Task Name
DEVELOP THE PRINTER RIGS
GENERATE RIG REQUIREMENTS
DEVELOP RIG EXPERIMENTS
DESIGN SALEM MODULES
DESIGN PRINTER STRUCTURE
DESIGN VARIABLE HOIST
DESIGN EXTRUDER
DESIGN CEMENT DELIVERY SYSTEM
DESIGN ELECTRICAL CONTROLS SYSTEM
PROCURE RIG COMPONENTS
PROCURE PRINTER STRUCTURE COMPONENTS
PROCURE VARIABLE HOIST COMPONENTS
PROCURE EXTRUDER COMPONENTS
PROCURE CEMENT DELIVERY SYSTEM COMPONENTS
PROCURE ELECTRICAL CONTROLS COMPONENTS
COMPONENTS AVAILABLE FOR BUILD
INSTRUCT & ASSEMBLE SALEM RIGS
START PRINTER ASSEMBLY PROCESS
GENERATE INSTRUCTIONS TO BUILD
MODULAR BUILD
BUILD VARIABLE HOIST RIGS
VARIABLE HOIST RIG 1
VARIABLE HOIST RIG 2
VARIABLE HOIST RIG 3
BUILD EXTRUDER RIGS
BUILD EXTRUDER RIG 1
BUILD EXTRUDER RIG 2
BUILD EXTRUDER RIG 3
BUILD SUPPORT STRUCTURE RIGS
BUILD SUPPORT STRUCTURE RIG 1
BUILD SUPPORT STRUCTURE RIG 2
BUILD SUPPORT STRUCTURE RIG 3
BUILD CEMENT SYSTEM RIGS
BUILD CEMENT SYSTEM RIG 1
BUILD CEMENT SYSTEM RIG 2
BUILD CEMENT SYSTEM RIG 3
BUILD CONTROL DECK RIGS
BUILD CONTROL DECK RIG 1
BUILD CONTROL DECK RIG 2
RIG ASSEMBLIES COMPLETE
PERFORM RIG TESTS
PERFORM EXTRUDER RIG TESTS
EXTRUDER RIG ER01
EXTRUDER RIG ER02
EXTRUDER RIG ER03
PERFORM HOIST RIG TESTS
HOIST RIG HR01
HOIST RIG HR02
HOIST RIG HR03
PERFORM SUPPORT STRUCTURE RIG TESTS
SUPPORT STRUCTURE RIG SR01
SUPPORT STRUCTURE RIG SR02
SUPPORT STRUCTURE RIG SR03
PERFORM CEMENT SYSTEM RIG TESTS
CEMENT SYSTEM RIG CR01
CEMENT SYSTEM RIG CR02
CEMENT SYSTEM RIG CR03
PERFORM CONTROL DECK RIG TESTS
CONTROL DECK RIG COR01
CONTROL DECK RIG COR02

4.4.3 Development Phase 3 – SALEM Earth Experiments

Development Phase 3 is a major body of work that completely validates and verifies the performance, safety, operability and longevity of the SALEM Printer for all Earth applications. This phase will deliver the bulk of design iteration and maturity and will be fed by data collected in the Rigs phase (DP2) and optimised accordingly. The bulk of computer analysis is completed on the printer as an integrated assembly in this phase.

The SALEM Printer will execute a myriad of print procedures to prove out the Print process including printing full structures and a Vertical Farm prototype. The SALEM development programme does not, however include the certification of the printed structures and so the work breakdown structure includes only print tests that prove the functionality and accuracy of the SALEM Printer.

The DP3 WBS delivers six full SALEM printers and tests plus several additional rebuild and tests to satisfy the experiments currently allocated to this development phase. By completing all six test sequences for Operability, Temperature, Safety, Maturity, Performance and final application (Vertical Farm Print) we can demonstrate and qualify the SALEM Printer to TRL8.

TRL 7	System Prototype demonstration in a relevant environment.
TRL 8	Actual system completed and “qualified” through test and demonstration.

Task Name
DEVELOP THE SALEM EARTH PRINTER
GENERATE SALEM EARTH PRINTER REQUIREMENTS
DEVELOP SALEM EARTH PRINTER EXPERIMENTS
DESIGN SALEM EARTH PRINTER
DESIGN PRINTER STRUCTURE
DESIGN VARIABLE HOIST
DESIGN EXTRUDER
DESIGN CEMENT DELIVERY SYSTEM
DESIGN ELECTRICAL CONTROLS SYSTEM
PROCURE SALEM EARTH PRINTER COMPONENTS
PROCURE PRINTER STRUCTURE COMPONENTS
PROCURE VARIABLE HOIST COMPONENTS
PROCURE EXTRUDER COMPONENTS
PROCURE ELECTRICAL CONTROLS COMPONENTS
INSTRUCT & ASSEMBLE SALEM EARTH PRINTERS
START PRINTER ASSEMBLY PROCESS
GENERATE INSTRUCTIONS TO BUILD
ASSEMBLE SALEM EARTH PRINTERS
PRINTER 1 - OPERABILITY & PERFORMANCE
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
PRINTER 2 - TEMPERATURE (PLUS PRINTER 1 BACKUP)
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
PRINTER 3 - SAFETY TESTING
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
PRINTER 4 - MATURITY
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
PRINTER 5 - OPTIMISATION & LIGHTNING
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
PRINTER 6 - VERTICAL FARM
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
PERFORM SALEM EARTH PRINTER TESTS
SALEM EARTH PRINTER EA01
SALEM EARTH PRINTER EA02
SALEM EARTH PRINTER EA03
SALEM EARTH PRINTER EA04
SALEM EARTH PRINTER EA05
SALEM EARTH PRINTER EA06

4.4.4 Development Phase 4 – SALEM Mars Experiments

The Mars printer phase is the final element of the printer development and will be by far the most difficult and expensive portion to complete, as it requires a manned mission to Mars.

The DP4 WBS includes an additional design iteration to the SALEM printer, to include features that will allow the machine to print successfully on Mars. This will include a general overhaul of the design to maximise product quality and resistance to extreme weather as well as a software iteration to include automatic procedures for a 2-person assembly and a more sophisticated heating system to withstand extreme cold.

To achieve TRL9 and thus, full certification of the SALEM Printer, one or more printers must be sent and operated on Mars to qualify as successful mission operation. This means that the WBS for DP4 includes transporting two SALEM Printers and four Astronauts to Mars and back.

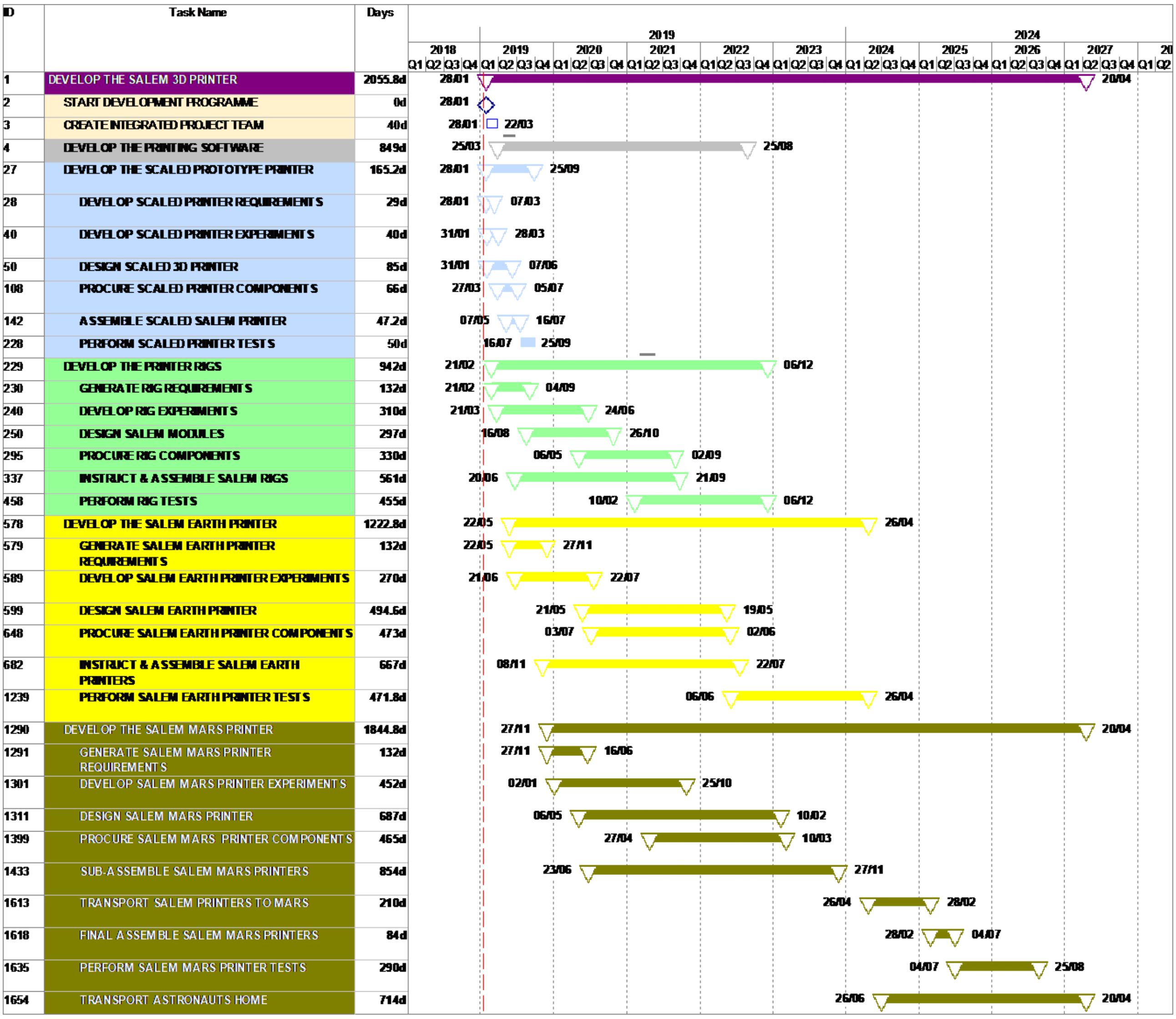
Task Name
DEVELOP THE SALEM MARS PRINTER
GENERATE SALEM MARS PRINTER REQUIREMENTS
DEVELOP SALEM MARS PRINTER EXPERIMENTS
DESIGN SALEM MARS PRINTER
DESIGN PRINTER STRUCTURE
DESIGN VARIABLE HOIST
DESIGN EXTRUDER
DESIGN CEMENT DELIVERY SYSTEM
DESIGN ELECTRICAL CONTROLS SYSTEM
PROCURE SALEM MARS PRINTER COMPONENTS
PROCURE PRINTER STRUCTURE COMPONENTS
PROCURE VARIABLE HOIST COMPONENTS
PROCURE EXTRUDER COMPONENTS
PROCURE ELECTRICAL CONTROLS COMPONENTS
SUB-ASSEMBLE SALEM MARS PRINTERS
START PRINTER ASSEMBLY PROCESS
GENERATE INSTRUCTIONS TO BUILD
ASSEMBLE SALEM MARS PRINTERS
PRINTER 1 - OPERABILITY & BASIC STRUCTURES
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
PRINTER 2 - VERTICAL FARM & BACKUP
MODULAR BUILD
BUILD VARIABLE HOISTS
BUILD EXTRUDER
NON-MODULAR BUILD
TRANSPORT SALEM PRINTERS TO MARS
FINAL ASSEMBLE SALEM MARS PRINTERS
SALEM MARS PRINTER 1 MA01.1
PERFORM SALEM MARS PRINTER TESTS
SALEM MARS PRINTER MA01
SALEM MARS PRINTER MA02
TRANSPORT ASTRONAUTS HOME

TRL 9	Actual system "proven" through successful mission and commercial operations.

To view the full WBS please refer to *Appendix 7 - SALEM Dev Programme* Project Plan.

4.5.0 Activity Schedule

Microsoft Project has been used to define the schedule of activities to complete the SALEM development programme. MS Project boasts a plethora of scheduling features that make it possible to plan, monitor and analyse complex projects with respect to time, cost and quality. With MS Project, the WBS has been broken down further into approx. 1700 individual activities that must be completed to achieve SALEM certification. These have been grouped using the Development Phases specified earlier in this proposal and are represented below as the colours blue, green, yellow and brown:



Snapshot of Microsoft Project Plan for Developing the SALEM Printer

The schedule assumes that the Development Phases will occur in parallel as much as possible to reduce overall development lead-time. Each successive Development Phase builds on data collected on previous phases. Because of this, each phase is slightly staggered from the previous. By completing development activities as soon as possible, we can expect to take approximately 8 Years from initiation to develop the SALEM printer.

4.5.1 Assumptions

The SALEM development schedule was planned left to right by breaking the WBS items down into a set of shorter, more tangible activities. Timescales for those activities were benchmarked against historical lead-times for Experimental Jet Turbine Projects I have previously managed, due to the core similarities in the project scale and manufacturing complexity. As the data used to determine these lead-times branch from experience within a large, century old corporation that is governed by cumbersome Aerospace regulations, the timescales presented in this schedule should be considered conservative.

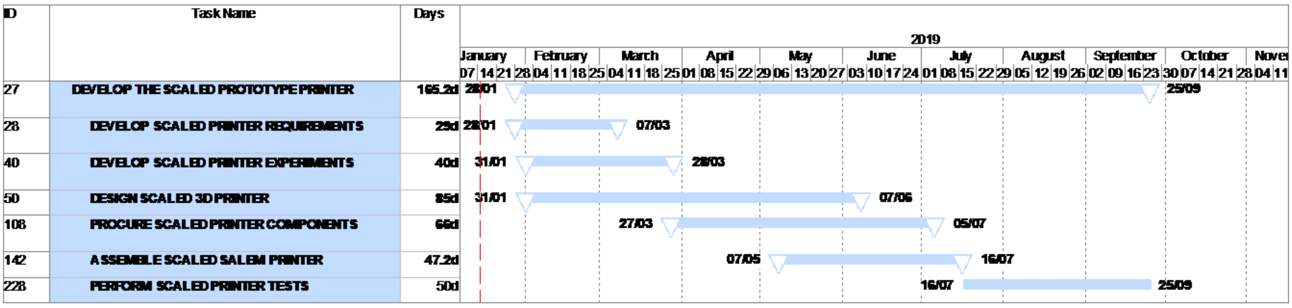
See Appendix 7 for full Microsoft Project Plan.

The SALEM Printer can be operated without anyone physically present which significantly reduces the likelihood of the development programme being slowed or stemmed by regulatory oversight until DP4 when SALEM Printers are launched to Mars. The schedule does not include the activities to achieve certification of printed structures such as Vertical Farms as this will require heavy governance and long-term proof of structural integrity and will take many years longer than the timescale of the SALEM development programme to complete. This should be considered an entirely separate programme of work.

The initial schedule indicates that it will take just over eight years to develop the SALEM Printer from concept, to a completed, mission validated technology. The development schedule does not include consideration for pre-production activities such as designing and building manufacturing facilities for SALEM Printers, or establishing a permanent supply chain. These activities should be considered after TRL6 has been completed (DP2) when it is clearer what the approximate manufacture requirements of the final product will be. Ideally pre-production would start shortly after the first successful tests of the full SALEM assembly which will occur during testing at DP3.

The Work Breakdown Structure has been standardised, as much as possible, across each development phase to include the same general activities for similar legs of work. The lead-times for each activity have been determined by factoring assumptions of how that task will be completed.

4.5.2 Development Phase 1 – Desktop Prototyping



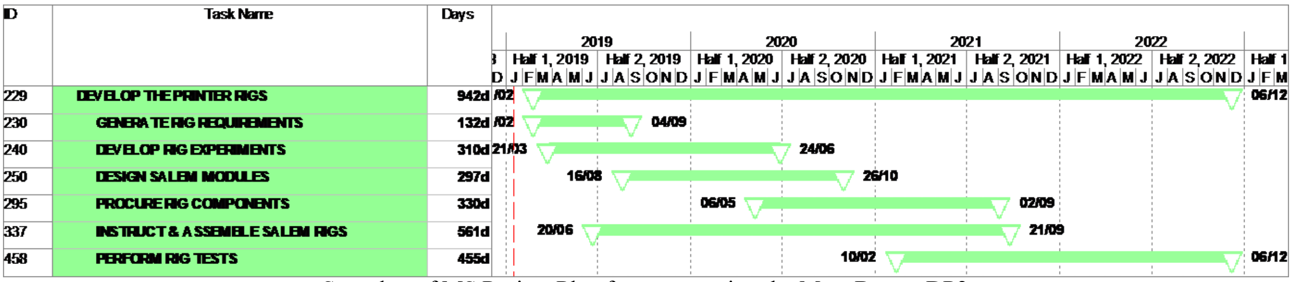
Snapshot of MS Project Plan for constructing the Mars Base – DP1

Desktop prototyping is the first phase of the SALEM development programme and will require the least investment of time and effort to produce tangible results. The schedule for DP1 has been drafted with the assumption that cost and time are more important than quality.

The requirements and experiments for DP1 will be relatively broad and will evolve with the design. Because the desktop printer is intended to be a cheap, rapid development phase with low investment requirements and will not represent the final product, there is not a great need for senior commitment on the experiments and design, which will reduce development time. DP1 will also largely re-use the current concept design as a starting point and should not need excessive development to function for the purpose of this prototype. For procurement of parts, the intent is to buy off the shelf where possible and manufacture in-house using 3D printing where applicable.

All of these factors combined make it possible to develop and test the scaled SALEM Printer within 6 months of beginning development providing early indication of the feasibility of the printer concept and potential design challenges. This phase of development can be started immediately upon initiation of the SALEM Programme and does not rely on any inputs outside of what has already been defined by this document and the concept SALEM Printer CAD Models.

4.5.3 Development Phase 2 – Rig Development



Snapshot of MS Project Plan for constructing the Mars Base – DP2

DP2 will provide validation of the individual modules of the SALEM Printer and is aimed at developing the printer design to component level definition. Rigs will most likely be full-scale and will represent the general form and function of the final printer but doesn't need to provide a high-performance finished product. This allows us to use low tolerance, fast make suppliers for procuring parts which will reduce manufacturing cost and time, but also quality.

With these assumptions it should be possible to complete DP2 and achieve TRL6 within 4 years of development, with almost half of this time allocated to testing the rigs. Additional rebuilds and part tests may be added to this schedule as and when new concerns present a need for further experimentation.

4.5.4 Development Phase 3 – SALEM Earth Experiments

ID	Task Name	Days		
578	DEVELOP THE SALEM EARTH PRINTER	1222.8d	22/05	26/04
579	GENERATE SALEM EARTH PRINTER REQUIREMENTS	132d	22/05	27/11
589	DEVELOP SALEM EARTH PRINTER EXPERIMENTS	270d	21/06	22/07
599	DESIGN SALEM EARTH PRINTER	494.6d	21/05	19/05
648	PROCURE SALEM EARTH PRINTER COMPONENTS	473d	03/07	02/06
682	INSTRUCT & ASSEMBLE SALEM EARTH PRINTERS	667d	08/11	22/07
1239	PERFORM SALEM EARTH PRINTER TESTS	471.8d	06/06	26/04

Snapshot of MS Project Plan for constructing the Mars Base – DP3

DP3 is the main body of development for the SALEM Printer and is scheduled to take approximately 5 years to complete. The DP3 design work will build on the design developed in DP2 to optimise for Earth applications. This is a crucial step in the design process and as such will require oversight and buy in from all engineering functions at each stage increasing the length of time to complete. Fast make suppliers may still be used in this phase, however manufactures will be required to finish components to specific and potentially challenging specifications which means longer lead-times than DP2 to procure parts.

The current experiments for DP3 will require at least 6 test vehicles with multiple rebuilds in between so testing is expected to take around 2 years. This includes full scale printed structures and long-term cyclic maturity testing.

4.5.5 Development Phase 4 – SALEM Mars Experiments

ID	Task Name	Days		
1290	DEVELOP THE SALEM MARS PRINTER	1844.8d	27/11	20/04
1291	GENERATE SALEM MARS PRINTER REQUIREMENTS	132d	27/11	16/06
1301	DEVELOP SALEM MARS PRINTER EXPERIMENTS	452d	02/01	25/10
1311	DESIGN SALEM MARS PRINTER	687d	06/05	10/02
1399	PROCURE SALEM MARS PRINTER COMPONENTS	465d	27/04	10/03
1433	SUB-ASSEMBLE SALEM MARS PRINTERS	854d	23/06	27/11
1613	TRANSPORT SALEM PRINTERS TO MARS	210d	26/04	28/02
1618	FINAL ASSEMBLE SALEM MARS PRINTERS	84d	28/02	04/07
1635	PERFORM SALEM MARS PRINTER TESTS	290d	04/07	25/08
1654	TRANSPORT ASTRONAUTS HOME	714d	26/06	20/04

Snapshot of MS Project Plan for constructing the Mars Base – DP4

DP4 is the longest phase of SALEM Printer development and is expected to take around 7.5 years to complete. Developing the Mars experiments is expected to take longer than the other phases due to the prohibitively high cost of late amendments. The tests will be carried out on Mars meaning that all tests *must* be defined and allocated well in advance of transporting the hardware and, due to the dangerous nature of the mission, any alterations to the agreed plan will potentially have a profound impact. The same logic has been applied to the design lead-time assumptions which is scheduled to take 3 years in total. The DP4 design is planned to build on lessons learnt and designs established in DP2 and DP3 but remodelled for extreme conditions far beyond those experienced on Earth.

Another factor extending the timescales of DP4 is that transporting the SALEM Printers to Mars will take approximately 150 days. This adds 300 days to the total development time to transport the Astronauts there and back. TRL9 can be considered passed on completion of the SALEM Mars tests which is planned to take 7 years from phase start.

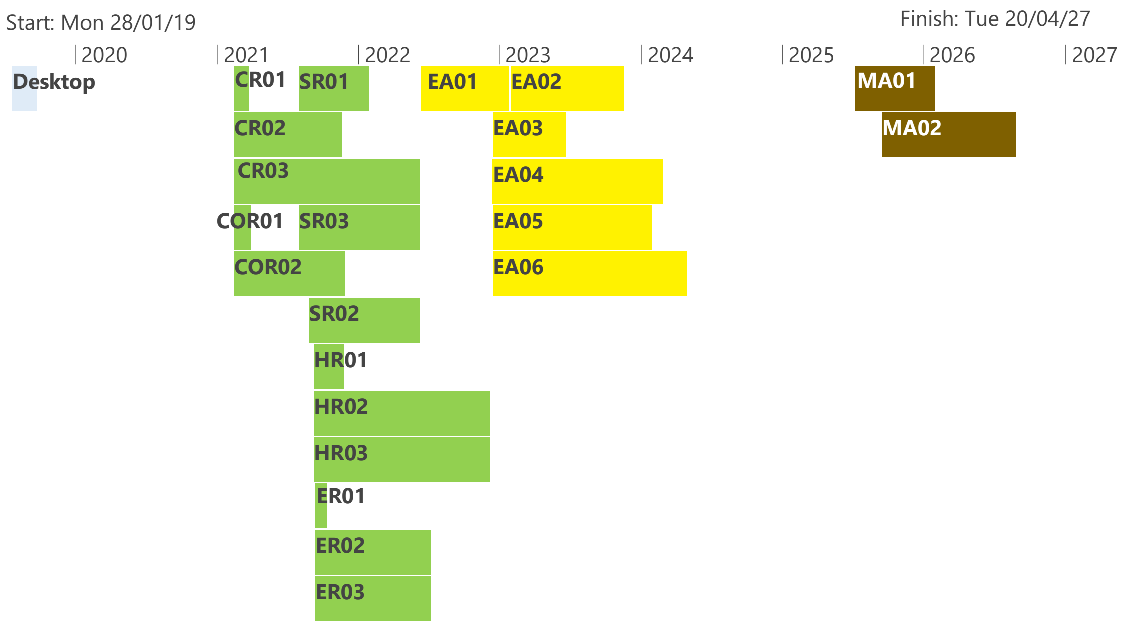
4.6.0 Development Test Plan

The Test plan for the SALEM Development programme is split into 4 distinct phases aligned to the development phases discussed in section 4.3.3. For DP1 only one test vehicle is planned, the desktop prototype. Further test vehicles are likely to be added to this phase, however any vehicle will be low cost and does not require a strict plan to deliver. The DP1 test vehicles will begin testing as soon as hardware is available.

For DP2 there are currently 14 test vehicles planned: 3 Cement system rigs, 3 Hoist rigs, 3 Extruder rigs, 2 Control Deck rigs and 2 Support Structure rigs. Support rigs will begin test around 2021 and will continue on for 2 years. For modules with three test vehicles, there will be a vehicle for basic operability, a vehicle for performance and safety testing and a vehicle for component failure tests.

DP3 consists of 6 test vehicles. EA01 will perform operability testing, EA02 will be for temperature and rain testing, EA03 for component failure tests, EA04 for maturity cycles, EA05 for optimisation and extreme weather testing and EA06 to produce a prototype Vertical Farm. This testing phase start will coincide with the tail end of rigs testing and will last for approximately 2 years.

The final phase, DP4, will consist of two test vehicles. MA01 will perform a series of single-floor structure prints and MA02 will be used to print a single multi-storey building, mimicking requirements for a vertical farm.



Cartoon Plan of Experimental Vehicle Tests for SALEM

4.7.0 IPT Accountabilities

Because the SALEM Printer Programme has a defined end goal that can be broken down and grouped into a series of projects (Development Phases), we can manage the whole Programme through Integrated Project Teams (IPT). For the purpose of this assessment we will assume that the only indirect resources required for our IPT is Project/Programme Management and Chief Engineer roles. All accounting, resource management, quality control and other indirect activities will be managed by the Project Manager, Programme Manager or Chief Engineers. For activities that will require massive collaboration to complete, such as launching the SALEM Printer and Crew to Mars, the resources required for launch will be considered as contractual barring the astronauts who will complete the Mars printing mission.

The individual resource groups of the IPT each resolve certain project accountabilities and are described below:

Resource Name
Fitter/Tester
Design Engineer
Stress Engineer
Project Manager
Development Engineer
Chief Development Engineer
Chief Design Engineer
Supply Chain Manager
Assembly Engineer
Software Engineer
Instrumentation Engineer
Astronaut

4.7.1 Resource Descriptions

Programme Manager

The Programme Managers role is to control and steer the programme of work and as such is accountable for any decisions about Cost and Time that have a significant impact on the key success factors and deliverables of the SALEM Programme. This includes decisions about resource delegation, increasing or decreasing scope and risk management. The Programme Manager will act as the representative of the Programme and will be tasked with reporting progress and challenges to the Programme Sponsor and other key stakeholders. The Programme Manager will define the requirements of the Development Programme in terms of cost and time.

Project Manager

The Project Manager(s) is the IPT lead and is tasked with delivering the SALEM development phases to defined (through the project management plan) cost and time targets. The Project Manager is empowered to agree scope change that affects the specific project by no more than 10% overall in terms of cost or time and acts as the communication line between the IPT and the Programme Manager. The Project Manager will also be responsible for monitoring and reporting on the projects progress, managing the budget and final release of finances to manufacturers and resources, as well as gaining commitment acceptance for planned activities and mitigating risk and hazards affecting the project.

Chief Design Engineer

The Chief Design Engineer manages the Design, Software and Stress Engineering groups and is responsible for ensuring that the SALEM Printer meets all design requirements in a simulated environment and will manage scope change to design intent and quality. A key success criterion for the Chief Design Engineer is ensuring that all design functions are working collaboratively and will act as the first port of call for escalation of design issues that cannot be rectified without impact to cost, quality or time.

Chief Development Engineer

The Chief Development Engineer is responsible for managing the validation and verification of the SALEM Printer programme. They manage scope change to experiments, test vehicles and assembly and are the responsible manager for the Development, Instrumentation and Assembly Engineers as well as the Fitter/Tester function. They will decide the number of individual test vehicles and the shape of the assembly and test programme of work and will also be accountable for the experiment assumptions. The Chief Development Engineer will be the first point of escalation for any assembly, test or experiment hazards that will affect quality, cost or time.

Design Engineer

The Design Engineer role is a core engineering role within the IPT and will be tasked with developing the design of the SALEM Printer through each development phase. Design Engineers will be aligned to a specific module of the printer such as Hoists, Extruder, Cement System etc and will utilise CAD Software to generate computer models of the printer and develop the Manufacturing drawings and design definition reports. During manufacture, assembly and test, the Design Engineers will be responsible for resolving issues pertaining to the printers' design and will work closely with the Supply Chain Managers to select suitable suppliers. The Design Engineers are also responsible for defining and steering the specific requirements of each printer module and will play a major role in defining the Bill of Materials for each test vehicle.

Stress Engineer

Stress Engineers are tasked with analysing the performance of the printer in simulated and physical environments. Working closely with the Design Engineers, the Stress Engineers will ensure that the Printer design will operate as envisioned. The Stress Engineers and Design Engineers' teams may be pooled into a multidiscipline team where design and analysis activities are shared and each engineer is responsible for a specific element of the printer. By keeping the two functions separate it ensures fewer people are making direct changes to the design and thus there is less chance of miscommunication causing anomalies or issues with boundary interfaces.

Software Engineer

The SALEM Printer software will be developed and programmed by the Software Engineer group. They will be tasked with proving the suspended Extruder concept and developing all electrical functionality of the printer. The Software Engineers will not design the physical control system but will be a key internal customer to the Design Engineers that will be tasked with that. During assembly, calibration and test the Software Engineers will act as guidance to the Fitter/Testers and will resolve any issues pertaining to software performance.

Development Engineer

Development Engineers are tasked with ensuring the validation and verification of the printer by defining and exacting the specific experiments to be completed on the desktop prototype, rigs and final assemblies. The Development Engineers will provide the instrumentation requirements necessary to certify the SALEM Printer and will resolve any issues presented in manufacture, assembly and test that pertains to experiment definition. The Development Engineers will specify the measurements required to certify the SALEM Printer and will work closely with Instrumentation Engineers to ensure the right type and quantity of data is collected in the vehicle tests. The Development Engineers are also responsible for writing the specifications and test schedules for each test vehicle.

Instrumentation Engineer

Instrumentation Engineers will design the instrumentation to deliver the data requested by the Development Engineers. The Instrumentation Engineers determine measurement type, specific parameter locations/lead-out and application methods for the instrumentation on each test vehicle. This function will be responsible for resolving any issues on build or test pertaining to the design and application of instrumentation hardware. The Instrumentation Engineers will also apply instrumentation to components and complete instrumentation rigging and checkouts.

Assembly Engineer

Assembly Engineers will define the method and sequence for assembling the SALEM Printer and as such will deliver the assembly instructions for each test vehicle. During assembly and test the Assembly Engineers will provide guidance to the Fitter/testers on correct assembly methods and will resolve any issues relating to Assembly. It may prove logical to pool the Assembly Engineer and Fitter/Tester resources as one team to improve resource levelling.

Supply Chain Manager

The Supply Chain Managers are responsible for procuring the bill of materials for each test vehicle and will work closely with the Design, Instrumentation and Stress engineers to ensure capable manufacturers are selected. This responsibility extends to ensuring that commitment is gained from manufacturers to deliver to the timescales set in the Project schedule. They will also be responsible for managing the financial transactions and delivery requirements of the procurement process and for communicating manufacture progress. This means that the Supply Chain Managers must foster close working relationships with manufacturers.

Fitter/Tester

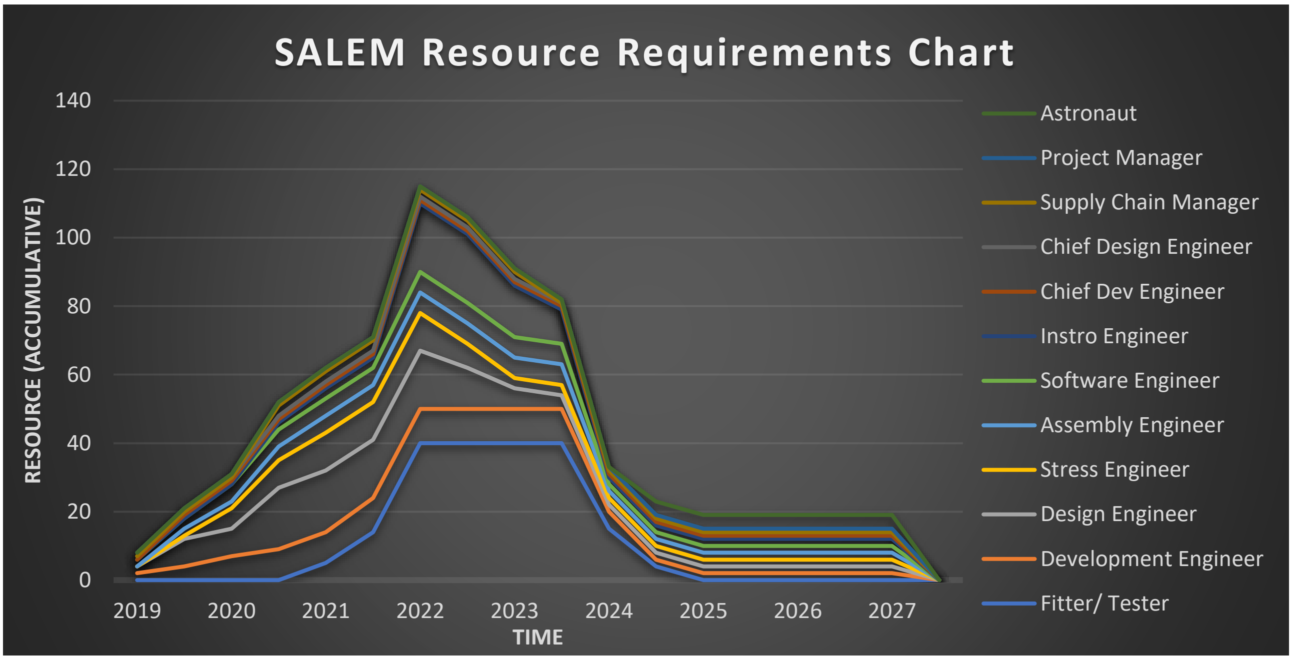
The Fitter/Testers are the hands-on function that will physically kit, build and test the SALEM Printers and rig assemblies. They will be responsible for raising concerns with the test vehicles during build and test to the relevant IPT member on the nature of the hazard, risk or complaint.

Astronaut

Astronauts will be necessary during DP4 in order to complete the Mars printing mission. The Astronauts will be required to transit to Mars with SALEM printers and complete structural prints on site. The Astronauts are accountable for verifying the SALEM Printer operation and 2-person assembly method in a real-world situation.

4.8.0 Resource schedule

The resource requirements for developing the SALEM Printer has been calculated through the 'SALEM Development' Microsoft Project Plan as discussed in section 4.5.0. Each activity in the MS Project plan has been aligned to one or more resource group discussed in the IPT Accountabilities section. For the majority of tasks, a predominant resource has been assigned, representing the main accountable function, but a percentage of time has also been added for other resources that will participate in some way in that activity. For example, the activity 'Generate Concept CAD Models – Support Structure' will predominantly be completed by a Design Engineer so has been given a 100% Design Engineer overhead. Development Engineers and Assembly Engineers will also have some input into the design so have been assigned a small percentage of work to this task too. By assigning resources in this way to every activity in the schedule we find the overall approximate resource requirements of the development programme:



SALEM Development Programme Resource Requirements

In this graph we can see that resource requirements start modestly in 2019 with Design, Stress and Development engineers expanding the fastest from 2019 to 2021. During this period the desktop prototypes will be completed and design/ development work will be the largest activity. In 2022 we see a spike in all resources, especially for fitter/tester resource. This is because it is the period of development with the greatest number of assembly and test activities underway at the same time which will require support from most other functions to resolve issues found during build.

From 2024 the resource requirements take a dive down to a minimum crew. This is because during this time DP2 & DP3 will complete development testing and DP4 will enter assembly. DP4 entails launching 4 Astronauts to Mars with SALEM Printers. during this period there will be a lot of time spent in transit therefore not requiring a large number of resources to maintain progress. When the Astronauts arrive on Mars, assembly and test of the SALEM Printer will entirely be carried out by the Astronauts themselves and resources maintained on Earth for this project will be largely there for advice and problem resolution. It is therefore possible to reduce the team down to one person per function for this mission (not including launch crew).

4.8.1 Development Phase 1 – Desktop Printing

DP1 is planned to be the least resource intense development phase with the largest amount of resource planned for modifying the design for desktop purposes. At this stage the IPT is to be kept to a minimum. The total hours for this phase equate to less than 1-person working full time. If DP1 is completed in isolation to the rest of the SALEM development programme it would be prudent to align 1 Design Engineer to complete this phase to design, procure, assemble and test the desktop printer. The hours aligned to programme management for oversight may instead be spent by the programme sponsor if DP1 is completed ahead of the start of the other development phases.

Resource Name	Work
Chief Design Engineer	0
Assembly Engineer	40
Design Engineer	787.4
Development Engineer	16
Project Manager	0
Programme Manager	40
Stress Engineer	40
Chief Development Engineer	0
Instrumentation Engineer	0
Fitter/Tester	40
Supply Chain Manager	0
Software Engineer	200
Astronaut	0
Total Hours	**1,123.4 Hours**

4.8.2 Development Phase 2 – Rig Development

A proper integrated team will need to be formed by the start of DP2 to manage the workload. This will include a dedicated team of designers to complete component level design on the SALEM Printer, as well as a team of development engineers to define and execute the experiments. At DP2, to save on resource overheads, it is assumed that all instrumentation will be bought off the shelf and there will be no special measurement requirements. With these assumptions it is permissible that the Instrumentation engineering work can be completed in tandem by the Development Engineers.

Resource Name	Work (Hours)
Project Manager	2,990.16
Programme Manager	5,468.6
Chief Design Engineer	1,912.8
Chief Development Engineer	2,300.4
Design Engineer	34,045.2
Development Engineer	27,430.8
Stress Engineer	13,674
Fitter/Tester	52,665.6
Assembly Engineer	8,433.6
Software Engineer	3,036
Supply Chain Manager	2,100
Instrumentation Engineer	0
Astronaut	0
Total Hours	**154,057 Hours**

Assembly of the Rigs is expected to be resource heavy given that there are 14 separate rig vehicles. In order to keep pace with the MS Project plan for DP2, fitter/tester resource will have to increase from approx. 9 staff in mid-2020, to over 27 by end of year.

4.8.3 Development Phase 3 – SALEM Earth Experiments

In DP3 the overall resource requirements are similar to DP2, however the dynamics are changed. At this phase the basic design of the printer will have been defined to component level and DP3 design work will be focused around optimising the printer. This means that the design requirements for this phase are less than DP2. In this phase the Instrumentation Engineer role is introduced to design the special test equipment and measurement devices. As The current experiments suggest the need for at least 6 full SALEM Printers, the fitter/tester resource level will also be slightly higher than for DP2.

Resource Name	Work
Project Manager	2,653.2
Programme Manager	5468.6
Chief Design Engineer	893.6
Chief Development Engineer	981.6
Assembly Engineer	9,002.8
Design Engineer	16,843.6
Development Engineer	19,042.4
Software Engineer	9,747.2
Stress Engineer	10,126
Supply Chain Manager	3,256
Fitter/Tester	57,220
Instrumentation Engineer	14,442
Astronaut	0
Total Hours	**149,677 Hours**

4.8.4 Development Phase 4 – SALEM Mars Experiments

The final development phase of the SALEM Printer will be the most resource heavy despite only featuring two test vehicles. The Mars printer design will run in tandem with DP3 to produce two separate printer designs. One that is capable of Earth based applications, and one that is capable of interplanetary applications. The SALEM Mars printer will be subject to much harsher working conditions than the SALEM Earth printer. It is therefore essential that detailed design studies are completed as part of the DP4 work-scope to ensure the intricacies of operating the SALEM Printer on Mars are well understood and the design reflects these nuances.

Resource Name	Work
Project Manager	4,199.6
Programme Manager	5,468.6
Assembly Engineer	14,837.2
Chief Design Engineer	4,107.2
Chief Development Engineer	3,525.2
Design Engineer	48,263.2
Development Engineer	27,541.2
Instrumentation Engineer	16,161.2
Software Engineer	15,971.2
Stress Engineer	24,895.6
Fitter/Tester	15,828
Supply Chain Manager	3,400
Astronaut	22,448
Total Hours	**206,646.2 Hours**

Assembly resource is split between Fitter/Tester staff and Astronauts as the final assembly of the DP4 test vehicles will be completed on Mars. Assembly Engineering requirements also increase at DP4 due to the requirement to design and validate a method of assembling the printer with a 2-person crew.

4.8.5 Resource Summary

After dissecting the MS Project plan for the SALEM Development Programme, we find the total hours required for each resource pool to be:

Resource Name	Work (Hours)
Fitter/Tester	125,753.6
Design Engineer	99,939.4
Stress Engineer	48,735.6
Project Manager	9,843
Programme Manager	16,445.8
Development Engineer	74,030.4
Chief Development Engineer	6,807.2
Chief Design Engineer	6,913.6
Supply Chain Manager	8,756
Assembly Engineer	32,313.6
Software Engineer	28,954.4
Instrumentation Engineer	30,603.2
Astronaut	22,448
Total Hours	**511,543.8 Hours**

The number of people working on the SALEM Printer programme at any one time will largely depend on how much time is planned to complete the body of work. If the intention is to complete the programme as soon as possible, number of staff could exceed 250 people on average, whereas if the programme is to be completed over 15 years it could be done with a workforce of 20 or less people.

For our analysis we have assumed a development time of approximately 8 years which will need an average of 35 staff to complete, however this requirement will not be levelled so neatly and to achieve the schedule, number of staff members will need to peak to nearly 120 full time during the majority of assembly and test in 2021.

See ***Appendix 9 – Resource Usage Graphs*** for resource requirements over time.

4.9.0 Cost Schedule

To determine the cost of the SALEM Development Programme we have to first define the total resource requirements and primary costs of each phase. The resource costs are calculated by applying an hourly rate to the resource requirements discussed in the previous chapter.

The hourly rate assumption for each function is given in the table to the right. This cost analysis does not include facility costs such as electricity overheads or factory rental, nor does it include costs for special software such as CAD Analysis packages. The licenses for this have been assumed under the parent company overheads.

Resource Name	Hourly Rate
Fitter/Tester	$32.44
Design Engineer	$38.93
Stress Engineer	$38.93
Project Manager	$58.39
Programme Manager	$64.88
Development Engineer	$38.93
Chief Development Engineer	$58.39
Chief Design Engineer	$58.39
Supply Chain Manager	$38.93
Assembly Engineer	$38.93
Software Engineer	$45.42
Instrumentation Engineer	$38.93
Astronaut	$77.86

4.9.1 Cost Analysis – DP1

After applying hourly rates to the resource requirements for DP1 we find the total resource cost for this phase to be approx. **$47,367.56**.

For DP1, the assumption is that development hardware will be manufactured on site through 3D printing methods or through off-the-shelf solutions where applicable. The main DP1 test vehicle will be a scaled desktop version of the SALEM Printer and it has been assumed that commercial, small scale electronics and 3D printing technology will be sufficient to manufacture and assemble a working prototype.

Under these assumptions, the total primary costs for DP1 has been projected to be in the region of $10,000. Including the costs associated with resource, we arrive at a total development cost of approx. **$57,267.56**

Resource Name	Cost
Chief Design Engineer	$0
Assembly Engineer	$1,557.20
Design Engineer	$30,653.48
Development Engineer	$622.88
Project Manager	$0
Programme Manager	$2,595.20
Stress Engineer	$1,557.20
Chief Development Engineer	$0
Instrumentation Engineer	$0
Fitter/Tester	$1,297.60
Supply Chain Manager	$0
Software Engineer	$9,084
Astronaut	$0
Total Resource Cost	**$47,367.56**

Item	QTY	Cost
3D Printer - Additive layer	1	$2,000.00
ABS Filament (1Kg Spool)	20	$500.00
Fasteners (Assorted)	1	$50.00
50-Watt motor	48	$2,400.00
Cables & Connectors (Assorted)	1	$50.00
Raspberry Pi 3	1	$100.00
Electronic accessories	1	$100.00
Laptop	1	$4,500.00
Sensors	1	$200.00
Total	**$9,900.00**	

4.9.2 Cost Analysis – DP2

The resource costs for DP2 jump up dramatically from DP1. At this point, the bulk of the initial component definition work is completed and the first full scale hardware demonstrations will be done. A full IPT will be required in order to develop and build a definitive case and understanding of the SALEM Printer modules. This includes a dedicated assembly/ Test team and a full suite of engineers.

To determine the cost of manufacturing all 14 rigs for this development stage, a general cost for hardware of $100/kg has been applied. This assumes that all parts will be manufactured using low cost materials and by cheap, third party, contract manufacturers and secondary forming techniques will be kept to a minimum. Using this high-level cost rate, we find that for the hardware only, the cost is in the region of $200,713.

Consideration needs to be made on the specific rigs and test equipment required to test the rig modules. A budget of $200,000 has been assigned for each of the required test cells. For the moment, it has been assumed that a test cell will be required for the Extruders, Hoists, Cement Systems and Support Structure. We will also need a range of special test equipment to perform the specific tests. This includes a cold box for freezing modules down to -200F, an electromagnetic radiation emission system and shielding for radiation testing, plus equipment to perform rain and hail ingestion testing. Costs for these SPTE items have been approximated against costs for similar SPTE used in Experimental Turbofan projects previously worked on.

Resource Name	Cost
Project Manager	$174,595.44
Programme Manager	$354,802.77
Chief Design Engineer	$111,688.39
Chief Development Engineer	$134,320.36
Design Engineer	$1,325,379.64
Development Engineer	$1,067,881.04
Stress Engineer	$532,328.82
Fitter/Tester	$1,708,472.06
Assembly Engineer	$328,320.05
Software Engineer	$137,895.12
Supply Chain Manager	$81,753
Instrumentation Engineer	$0
Astronaut	$0
Total Resource Cost	**$5,957,436.69**

Module Name	Cost
Extruders	$21,114
Hoists	$15,255
Support Structure	$116,652
Cement System	$38,892
Consoles	$8,800
Total Component Cost	**$200,713.00**

SPTE Item Name	Cost
Extruder Test Bed	$200,000
Hoist Test bed	$200,000
Cement System Test Bed	$200,000
Support Structure Test Bed	$200,000
Cold Box	$1,000,000
Rain & Hail System	$500,000
Radiation System	$1,500,000
Instrumentation	$280,000
Instro Measuring Devices	$560,000
Total Component Cost	**$4,640,000.00**

Finally, a number of instrumentation parameters and measuring devices will be required for the tests. A cost of $200 per parameter has been applied for this and it has been assumed that each rig will require 200 parameters on average. If we add the costs of resources, hardware and SPTE for DP2 we find the total cost of development to be approximately **$10,798,149.69.**

For a full cost breakdown see **Appendix 10 – DEV Primary Costs**

4.9.3 Cost Analysis – DP3

The cost of resource for development at DP3 will be similar to DP2. This is because the bulk of component definition work will be completed at DP2 and DP3 is largely for refinement and performance. Design engineer costs will be reduced at DP3 for this reason, however, the number and scale of assembly activities will be much larger at this development stage so build/test associated resource costs are higher for DP3 than DP2. This development phase also requires a much higher level of experiment development so costs for Development engineering and Instrumentation engineering are elevated.

Resource Name	Cost
Project Manager	$154,920.35
Programme Manager	$354,802.77
Chief Design Engineer	$52,177.30
Chief Development Engineer	$57,315.62
Assembly Engineer	$350,479.00
Design Engineer	$655,721.35
Development Engineer	$741,320.63
Software Engineer	$442,717.82
Stress Engineer	$394,205.18
Supply Chain Manager	$126,756.08
Fitter/Tester	$1,856,216.8
Instrumentation Engineer	$562,227.06
Astronaut	$0
Total Resource Cost	**$5,748,859.78**

The DP3 test plan includes 6 full SALEM Printers as test vehicles and is intended to produce results to determine performance of the printer. This means that component manufacture quality will be of much higher importance than at DP2. For this reason, it has been assumed that at this stage, components will cost approx. $2,000/ kg. This means an investment of more than $22 million will be required for DP3 hardware.

Module Name	Cost
Extruders	$844,560
Hoists	$610,200
Support Structure	$18,587,712
Cement System	$1,555,680
Consoles	$528,000
Total Component Cost	**$22,126,152.00**

The special test equipment requirements for DP3 will be considerably higher than DP2 largely due to the scale and size of equipment needed. For instance, the cold chamber for rig tests only needs to be a few meters wide, whereas the cold chamber DP3 needs to be big enough to fit a fully assembled Printer inside. There is also a need for a costly test chamber to simulate earthquakes and other natural disasters and the intention is also to generate a prototype Vertical Farm as part of the test process which will also require a large investment. With SPTE, Resource and Hardware costs considered, we can expect a cost of **$85,615,012** to deliver the DP3 development phase for the SALEM Printer programme.

SPTE Item Name	Cost
Test Land	$600,000
Vacuum Chamber	$15,000,000
Crosswind Chamber	$2,000,000
Rain & Hail System	$1,000,000
Cold Chamber	$8,000,000
Earthquake Simulation Chamber	$12,000,000
Vertical Farm Components	$10,500,000
Instrumentation	$7,200,000
Instro Measuring Devices	$1,440,000
Total Component Cost	**$57,740,000.00**

For a full cost breakdown see **Appendix 10 – DEV Primary Costs**

4.9.4 Cost Analysis – DP4

DP4 will be the most expensive development phase on all fronts and as this stage will require printing to be completed on Mars, there will be no real opportunity for rework of parts should an issue arise on build. For this reason, more time and consideration must be taken to ensure the design is as robust and defined as possible. There will also be a significant resource cost incurred at this stage for Astronauts to assemble and operate the Printer on Mars.

There is not a major volume of hardware required for the DP4 tests, with only two test vehicles currently planned, however component cost will be orders of magnitude more than DP3 due to the fact these prints will be completed on Mars under extreme conditions, therefore requiring more exotic materials and advanced secondary processes to complete. The assumption has been made that components will cost on average $15,000/kg at this stage.

The main SPTE expense for DP4 will be the Starship rockets required to transport the Astronauts to Mars and back. One Starship will transport the Astronauts, SALEM printer, cement and survival equipment, whilst a second Starship will deliver enough fuel to return one Starship with crew home. Each Starship is expected to cost $150,000,000. Instrumentation and Measuring equipment will also carry significant costs due to the high-performance requirements on Mars.

Resource Name	Cost
Project Manager	$245,214.64
Programme Manager	$354,802.77
Assembly Engineer	$577,612.20
Chief Design Engineer	$239,819.41
Chief Development Engineer	$205,836.43
Design Engineer	$1,878,886.38
Development Engineer	$1,072,178.92
Instrumentation Engineer	$629,155.52
Software Engineer	$725,411.90
Stress Engineer	$969,185.71
Fitter/Tester	$513,460.32
Supply Chain Manager	$132,362.00
Astronaut	$1,747,801.28
Total Resource Cost	**$9,291,727.48**

Module Name	Cost
Extruders	$2,111,400
Hoists	$1,736,100
Support Structure	$56,700,480
Cement System	$3,889,200
Consoles	$1,320,00
Total Component Cost	**$65,757,180.00**

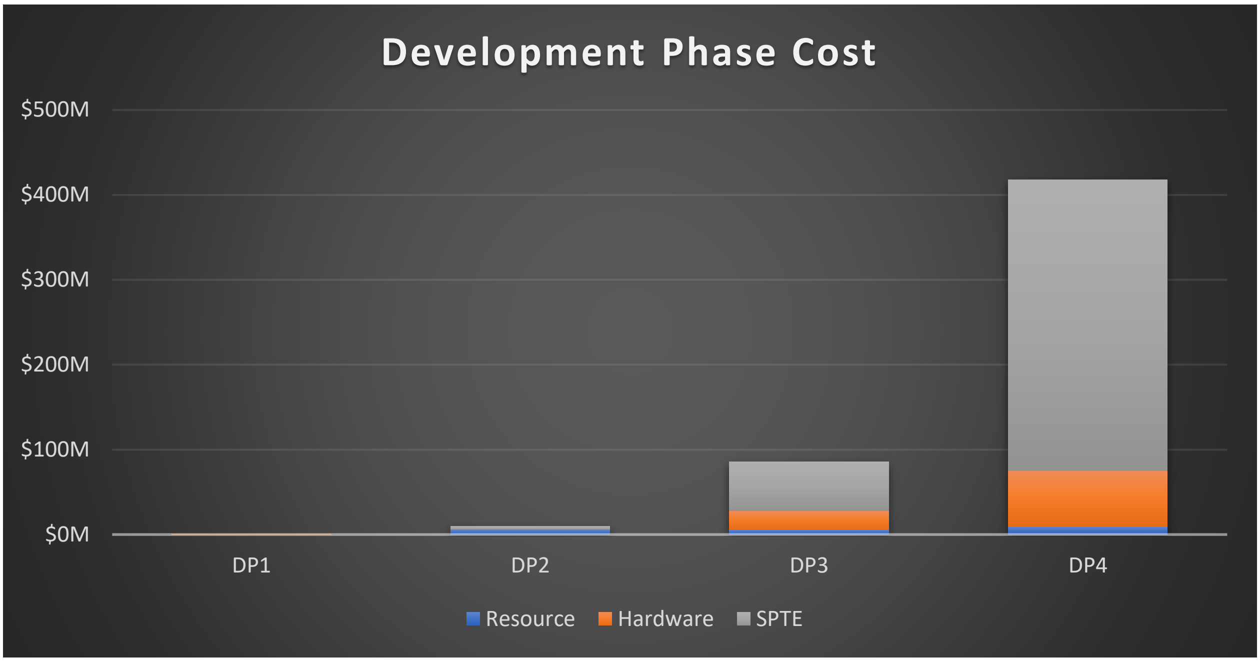
SPTE Item Name	Cost
Starships	$300,000,000
Vertical Farm Components	$10,500,000
Instrumentation	$30,000,000
Instro Measuring Devices	$2,400,000
Total Component Cost	**$342,900,000.00**

The total cost to complete DP4 of the SALEM Printer development programme would be approximately **$417,948,907** under these assumptions.

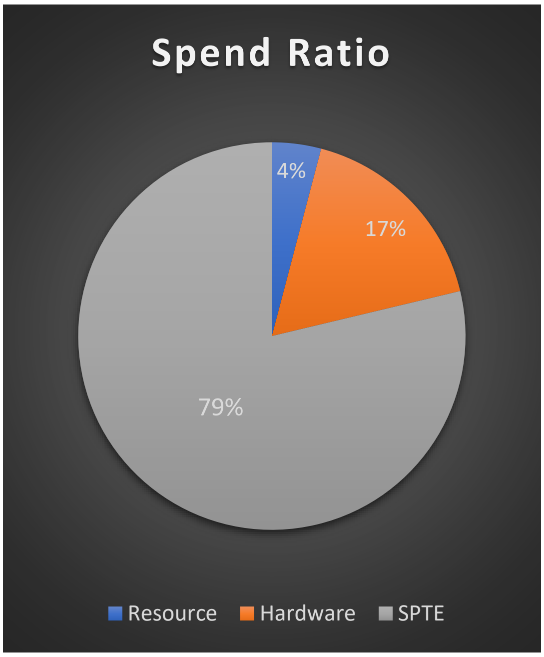
For a full cost breakdown see **Appendix 10 – DEV Primary Costs**

4.9.5 Cost Analysis - Conclusion

A number of conclusions can be made from this information concerning the cost of the SALEM Printer development Programme. A cost of approx. $514.5 Million will be required to develop the printer to the point that it can be used for off-world applications such as building a permanent base on Mars. The vast majority of the development costs (98%) will be spent during DP3 and DP4, with DP4 accounting for more than 81% of development costs alone. This is because nearly 60% of the total cost is associated with the cost of launching 2 Starships to Mars.



If the main goal of the SALEM development is to turn a profit, then at the end of DP3 the SALEM Printer is expected to be sufficiently developed to begin service on Earth, meaning DP4 could be omitted and the programme would still reap considerable financial benefits for the development to that point. However, if the main prerogative of the SALEM Printer development is to expand humanities potential to grow outside of Earth, then DP4 is essential.



As the overhead cost for delivering the printers to Mars is so high and the actual weight of the package to be delivered is much lower than the Starship capacity, it would make more sense to integrate the DP4 tests into a multipurpose Mars mission rather than achieve the development phase as an isolated mission. This would help offset the financial burden of completing the mission and certifying the printer to TRL9.

Without taking into account the cost of the Starships, SPTE still makes up the majority of expenditure (49%). This is because recreating conditions comparable to Mars will require a significant amount of bespoke equipment to achieve and the printer must be robust enough to withstand the harshest, most extreme weather conditions, necessitating an array of novel testing equipment.

4.10.0 Conclusion

"The individual is ephemeral, races and nations come and pass away, but man remains" - Nikola Tesla

At some point, we will all pass into the great unknown. There are many theories and beliefs as to what happens when we go, but one thing is all but certain. Mankind will continue on. Continue on pushing the boundaries of science and technology, fervently chipping away at the mysteries of existence and expanding the reach of what we can call home. Not for the glory and benefit of one, but for all. For the hopes that the world we leave behind, might be better than the one we entered, so that our children and their children would be blessed with the opportunity to pass an even greater opportunity on to the ones that follow. This inherent nature of man to unify and overcome is the cornerstone of what it means to be human and is the driving reason for all the blessings we share as a species today. It is the reason our distant ancestors were able to leave the jungles, build great civilisations and take the mantle as dominant life on Earth. But it is also the reason why we all share the burden of our mistakes and the responsibility of working together to overcome each new challenge we inevitably end up creating.

Climate Change is not and should not be a problem that is acceptable to pass to our successors, but a challenge that we can overcome and adapt to by working together, as we always have, toward something bigger than any one person, race or nation. The purpose of this proposal was to prove that the SALEM concept could feasibly provide a solution for future proofing several key functions of modern society.

The potential applications for the SALEM Printer within construction is limited only by the imagination of the architect and the laws of physics. It will make it possible to rapidly produce high quality, complex structures of virtually any size and shape and with materials found in abundance on Earth and Mars for a fractional cost to traditional methods. The SALEM Printer comes with a promise of revolution and evolution to how we build homes, produce food and will provide the essential tooling to one day colonise the stars.

In this proposal we calculated how this technology could allow us to construct high rise structures at such a fractional cost to traditional methods, that it would be feasible and profitable to produce industrial scale, purpose built Vertical Farms for the first time in history. We discovered that these Farms could be built so quickly and efficiently thanks to SALEM, that it may even be possible to completely eradicate world hunger and establish a permanent, sustainable food source for the entire planet in as little as four decades. We found that, with potentially as few as 20 people, 15 Starships and the SALEM Printer concept, we could create the infrastructure for a 2000-person Mars colony, offering humanity with a lifeline should anything happen to Earth.

We also discovered that all of this could be done in the course of a single generation.

One life time.

Ours.

5.0.0 References

5.1.0 Pictures

Figure 1
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Figure 2
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Figure 3
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Figure 4
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Figure 7
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Figure 8
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Figure 9
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5.2.0 Statements & Figures

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