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MOSS

Moon Outpost Smart Structures

Executive summary

The MOSS Project is a multidisciplinary initiative aimed at developing an advanced lunar outpost concept for future human missions. It focuses on reducing reliance on Earth resources through In-Situ Resource Utilization (ISRU) using lunar regolith. The project seeks to enhance the Technology Readiness Level (TRL) of ISRU techniques for constructing smart structures on the lunar surface, including sensor-embedded tiles and bricks.

The initial task involved identifying optimal lunar locations based on factors like sunlight exposure and temperature range. Utilizing data from the Lunar Reconnaissance Orbiter (LRO), a comprehensive study focused on the Shackleton crater near the Moon's southern pole, leading to the creation of "The Lunar Map" at a scale of 1:100,000.

Once the location was determined, the next phase included selecting construction techniques. An innovative material was proposed, combining thermoplastic polymer (PEEK) with lunar regolith to minimize power requirements. This blend achieved a flexural strength of 14.6 MPa with 15 wt% binder content, though it exhibited brittle behavior.

Initial construction steps involve fabricating a landing pad for human safety and resource supply, featuring walls to protect against dust and structural stability. Tiles for the landing pad utilize a hexagonal shape for easy manufacturing and stackability, adding redundancy for repairs after potential impacts. Finite element simulations validated the tile design, determining maximum safe landing speeds between 0.1 to 0.7 m/s.

A study on power sources concluded that nuclear fission reactors are preferable due to their high power output and independence from light conditions. Preliminary designs for a nuclear plant for a six-person settlement included a power budget of 65 kWe and considerations for regolith shielding to reduce safety distances.

Overall, the MOSS Project represents significant progress toward a self-sustaining lunar base, focusing on innovative technologies and practical solutions for long-term human operations on the Moon.

Key Words

Lunar outpost, In-Situ Resource Utilization (ISRU), lunar regolith, sustainability, space exploration, Human spaceflight, Moon, FBG

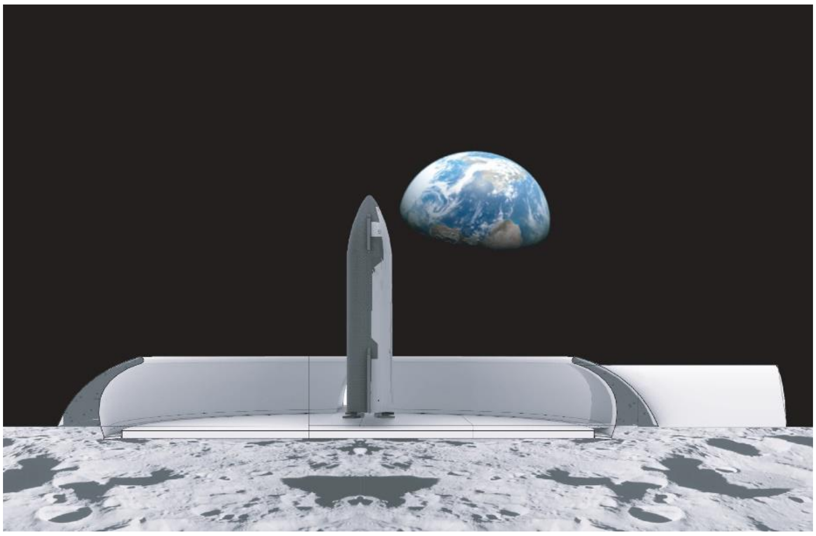
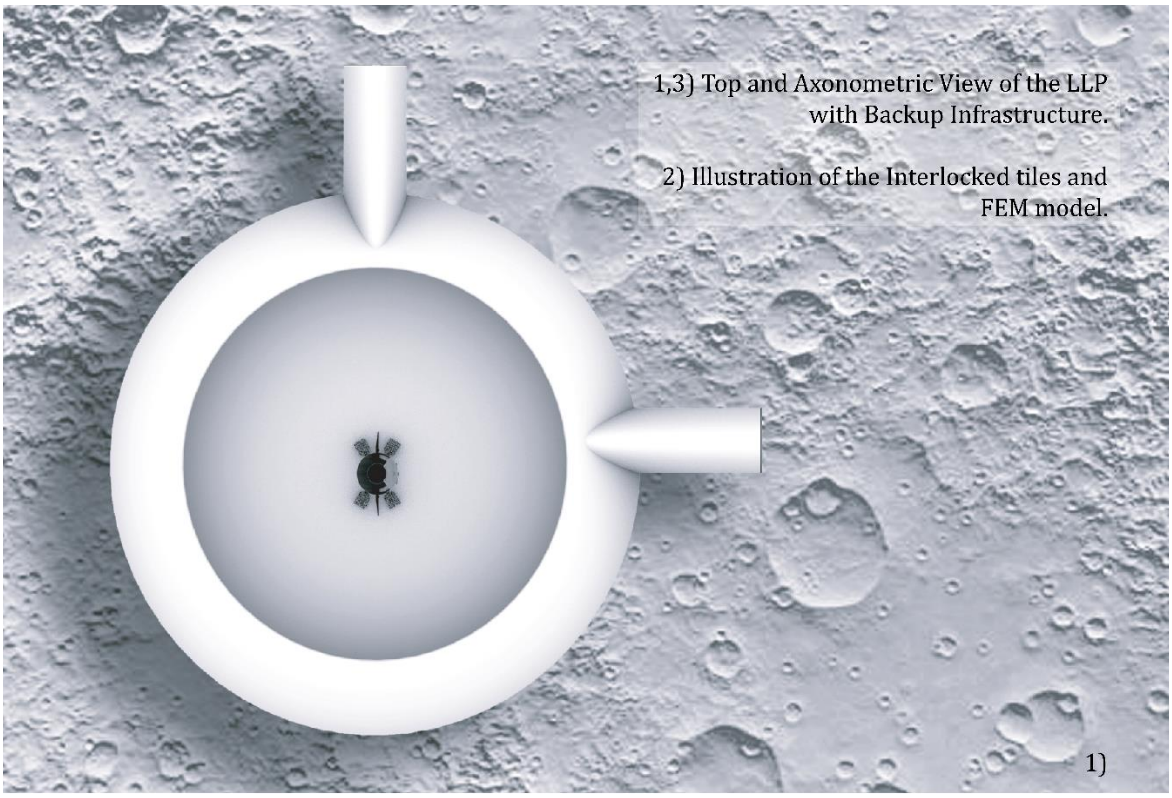
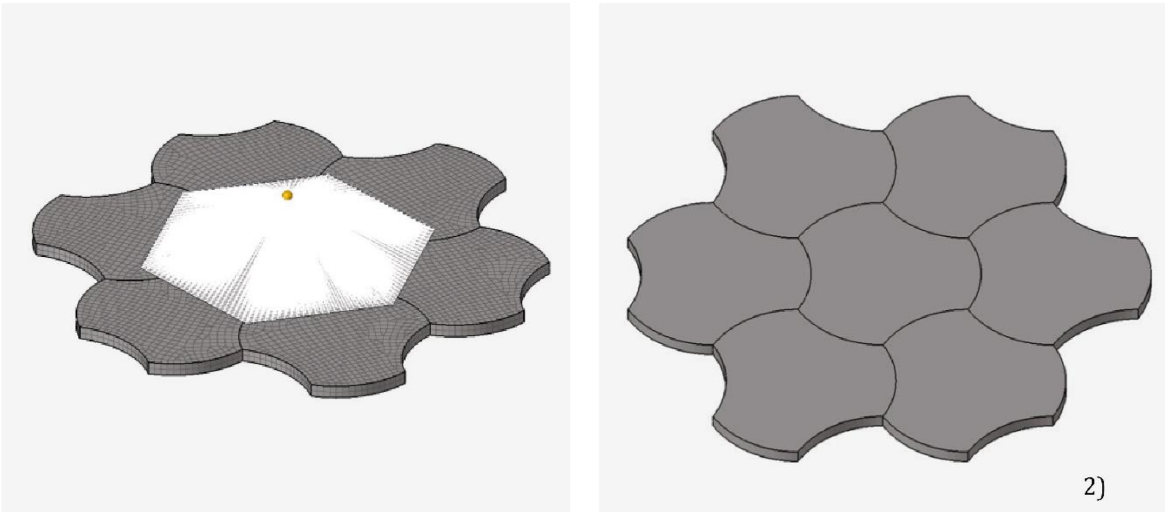


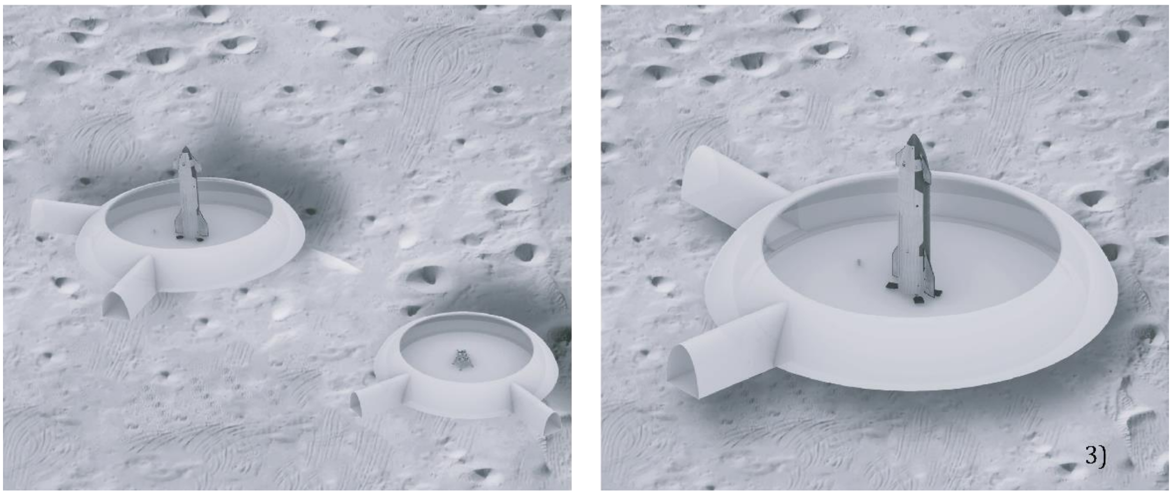
Figure 1: Section of the Lunar Landing Pad (LLP).



1,3) Top and Axonometric View of the LLP with Backup Infrastructure.

2) Illustration of the Interlocked tiles and FEM model.





Project description written by the Principal Academic Tutor

The Moon Outpost Smart Structures (MOSS) Project has a multidisciplinary research initiative aimed at establishing a sustainable lunar infrastructure using In-Situ Resource Utilization (ISRU) technologies. The primary focus was to develop a lunar outpost designed to reduce at minimum the dependence on Earth-based resources by utilizing lunar regolith for construction, particularly in manufacturing building blocks integrated with smart sensors. These sensors monitor parameters like temperature and structural integrity. The project has involved students from ASP tutored by Researchers of DLR (German Aerospace Center), ESA EAC (European Space Agency) and University of Derby. This project has proved the outstanding capability of a multidisciplinary team with expert from different stem branches such as Aerospace Engineer, Material Scientist, Architect and so on. Key aspects of the project has included:

1. **Site Selection:** The Shackleton crater near the lunar South Pole was chosen among other possible destination for the outpost for its favorable sunlight exposure, communication coverage, and potential water ice deposits.
2. **Construction Techniques:** The project proposes using a composite material made from lunar regolith and polyether ether ketone (PEEK), a thermoplastic polymer. This composite is lightweight, strong, and can be manufactured on-site, making it ideal for constructing tiles that form essential infrastructure, such as a landing pad. The tiles are designed to be stackable, facilitating repair and adaptability in harsh lunar conditions.
3. **Energy Sources:** Nuclear fission reactors were identified as the most suitable power source for the lunar outpost, after a comparison with solar panels, providing continuous energy independent of the lunar day-night cycle. A power budget of 65 kWe was established to meet the needs of a six-person settlement.
4. **Landing Pad Design:** A critical early step in the project is building a lunar landing pad (LLP) from interlocking tiles. This pad is designed to withstand landings of spacecraft like the European Large Logistic Lander. The structure also provides protection against lunar dust and micrometeorite impacts.

In conclusion, the MOSS project represents a milestone as a potential innovative approach to building sustainable lunar infrastructure leveraging local resources and cutting-edge technologies. The research publication that will be extracted will testify the solid contribution provided by this team to this challenging goal.

Team description by skill

The team is composed of seven members:

- **Marco Agozzino** is a Materials and Nanotechnology Engineer and contributed to the analysis of the polymer-regolith blend and collaborated with Armando in the interpretation of the results of the FEM simulations.
- **Karim Almatari,** a Sustainable Architect who's critical role in proposing a three staged scalable framework for the projects future developments, together with Jenna they analyzed the existing literature on the requirements for the existence of life on the moon and proposed a prototype for the an array-able shape of the brick to later be modified by the engineers to further develop our research.
- **Jenna Ashraf Hussein Tawfik,** who focuses on Architecture for sustainability, played an important role in developing the different stages of the spaceport development masterplan and 3D model thank to her experience using 3D modeling software, allowing us to develop the final design and structure of the outpost.
- **Sara Fesa** is an Interior Designer, she collaborated architects Karim and Jenna in the research and final presentation of the drawings that illustrate the designed structure. developed conceptual renderings of some interior spaces of the lunar base and assembled graphics to present a visual timeline of the project's implementation.
- **Michele Marrone** is a Space Engineer, he contributed by researching solutions for the landing pad and collaborated with Luca on selecting the power supply, followed by the design of the nuclear reactors.

- **Luca Pasqualin,** an Aerospace Engineer with expertise in Aeronautical Mechanics and Systems, covered an essential role in assessing the overall power budget of the settlement, in selecting the nuclear energy as main power source through comparative analysis and in designing and coding an optimized nuclear-plant model. He collaborated with Michele, who was remarkable in demonstrating the non-feasibility of solar arrays as primary power source and in carrying out a comprehensive study of existing nuclear solutions to fit in with the theoretical results of the model developed.
- **Armando Pastore** is an Aerospace Engineering student who primarily focused on examining the mechanical response of structural elements manufactured from a polymer-regolith blend via explicit FEM numerical analysis. Together with Marco, he interpreted the simulation results, extracting patterns and trends that helped predict the optimal mixture ratio to meet the structural requirements for a Moon landing, while minimizing dependence on Earth.

Goal

The **MOSS project** aims at designing the future Lunar outpost by means of a comprehensive approach. In particular, the goal is to provide a solution that views the outpost as an integrated system rather than a collection of individual components.

Consequently, all solutions developed must be compatible with the lunar environment using In-Situ Resource Utilization (ISRU) techniques, and equally important, they must ensure seamless compatibility among them.

Understanding the problem

In order to adequately frame the problem we had to analyze the challenges of constructing smart structures on the lunar surface, using minimum materials transported from earth, we meticulously evaluated the essential requirements for sustaining life. This involved a comprehensive review of existing literature and research to determine the necessary resources and spatial distribution for human habitation to define a clear program for our structure. Through this analysis, we identified the opportunity to develop a lunar spaceport that facilitates efficient transport to and from Earth built sustainably. That meant using resources available on the moon as much as possible.

Building a settlement on the Moon via in-situ resource utilization (ISRU) techniques presents a complex and multifaceted challenge. The primary goal is to establish a sustainable human presence by harnessing local lunar resources to minimize reliance on Earth-based supply chains. Key challenges include extracting the regolith and manufacturing the structural elements. Another issue is the choice of the manufacturing technique, performing a tradeoff between energy efficiency, and structural performances of the produced elements.

Another important issue to tackle is the provision of power to ensure a permanent human presence in the outpost. As a matter of fact, both the manufacturing of tiles and the functioning of the entire settlement must rely on an efficient power source. After some considerations, by comparing data already available in literature with experimental ones supplied by Politecnico of Turin, a power budget value of 65 kWe, safety factors included, was determined, thus an appropriate main source of energy needed to be selected, in compliance with the harsh environment requirements.

Exploring the opportunities

Architecturally speaking our approach resulted in a scalable solution, designed to evolve alongside the growth of a lunar colony, addressing both immediate needs and future expansion stages. This strategic framework not only highlights the feasibility of our project but also paves the way for innovative architectural solutions on the Moon which can also apply to construction in extreme environments on Earth.

With regards to construction execution the lunar surface is covered by a layer of fine sand-like material that is called regolith. Given its abundance, it is only natural that any successful ISRU building technique should employ it as the main building material. ISRU techniques for constructing lunar settlements can be classified into two main approaches based on how loose regolith is transformed into solid structural materials. The first involves thermal processing, where regolith is melted or surface diffusion between grains is induced to form a solid material. The second uses organic or inorganic binders to bind the regolith. Both methods commonly utilize 3D printing to create hollow structures filled with loose regolith. Each approach has pros and cons: sintering is energy-intensive, while the use of binders requires substantial materials to be transported from Earth.

The solution we have envisioned relies on a compromise, where a thermoplastic polymer (PEEK) is blended with lunar regolith and compressed in a heated mold. This technique allows to achieve sufficient strength with a reduced binder content and electric power and is conducive to a straightforward production process that can be easily automated. Furthermore, due to the nature of the chosen polymer, structural elements can be ground and reshaped once they reach the end of their service life.

As regards the power source selection, a comparative analysis to decide whether solar arrays or nuclear fission reactors fitted better in the described scenario was conducted. After some calculations, nuclear energy was chosen as primary source, for two main reasons: it is not affected by day-night cycle on the moon and the specific power delivered is one order of magnitude higher, due to the absence of batteries as storage system. However, the dose radiation emitted by reactors is of primary concern for health hazard, thus in the final solution a regolith shield will be introduced.

Generating a solution

The first task of the project was to find the best location on the lunar surface in terms of sunlight exposure, communication coverage, temperature range and Topography. For this endeavour, various tools were employed. Using data from the Lunar Reconnaissance Orbiter (LRO), the team performed selenography - an in-depth study of the lunar surface - focusing on the Shackleton crater located near the Moon's southern pole. The data from the LRO made mapping the surface according to the previously described criteria. Based on the analysis done, "The Lunar Map" was created at scale 1:100 000 where the design and distribution of the spaceport can be visualized.

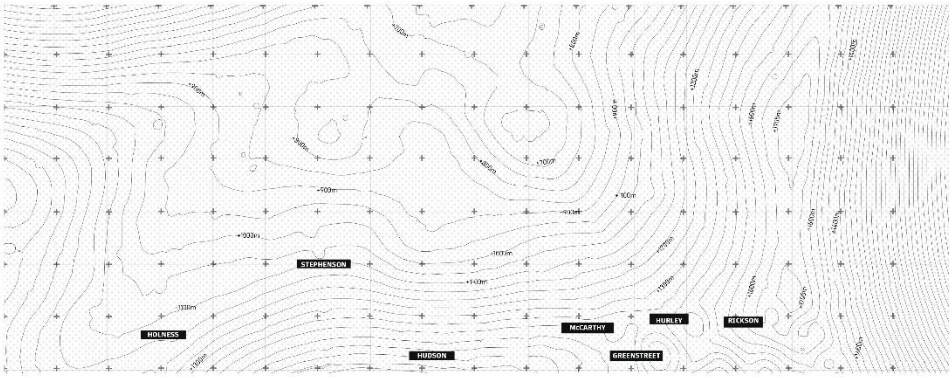


Figure 2: Map showcasing lunar topography, spot elevations and potential project locations (1.0 x 1.0km grid).

The next phase was to estimate the requirements for a progressively growing stable population on the Moon, from a single outpost to a lunar base and, ultimately, to a self-sufficient colony. This analysis was performed through a deep literature investigation that involved 25 articles regarding the concept of future human outposts on the Moon. The final result is thus a detailed footprint that provides a visualization of the project's placement once it is implemented onto the designated site. In this sense, a diagram has been designed to show the progress of the road-map that has been envisioned for the mission.

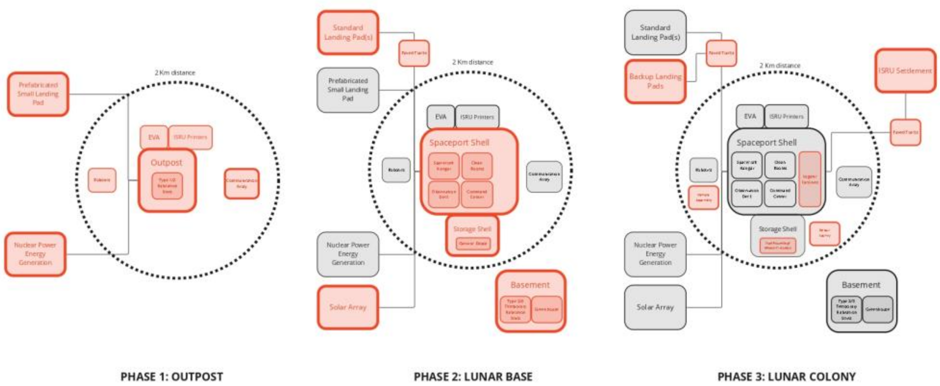


Figure 3: Compositional diagram illustrating the design of the distribution program divided into three distinct phases.

Just like Neil Armstrong's *"small step,"* the authors believe that a challenging project such as the construction of a future human outpost on the Moon should begin with the fabrication of a safe landing pad, allowing safer landings for the transfer of both goods and astronauts. For this purpose, this work focuses on studying the material properties of a regolith-PEEK blend in various proportions, examining key mechanical properties and the effects of manufacturing conditions on these properties.

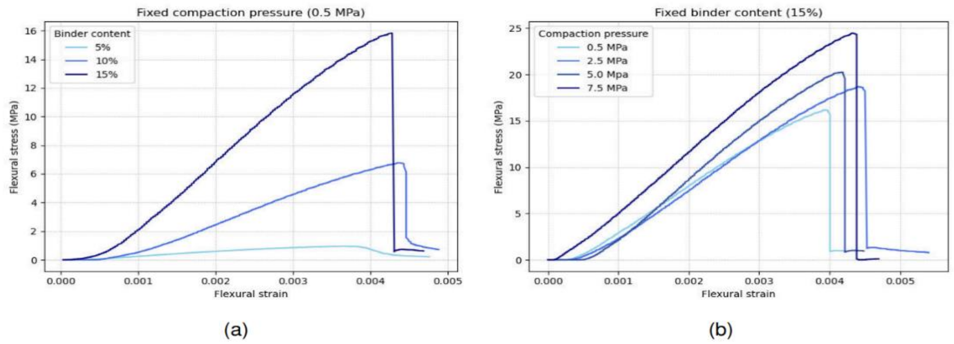


Figure 4: Flexural strain-stress curves shown by the specimens for fixed compaction pressure (a) and binder content (b).

Once the mechanical properties have been studied, the structural response of a landing pad built with the selected blend is analysed via FEM explicit numerical simulations. The goal is to identify the minimum amount of binder to bring from Earth to sustain landing velocities in range 0.1 - 1 m/s, which is identified as the most plausible range of future landing speeds on the Moon (Capolupo and Rinalducci, 2024). The results are summarised in tha table below:

DoE run no.	1	2	3	4	5	6	7	8	9	10	11	12
v_{max} [m/s]	0.02	0.05	0.12	0.15	0.22	0.3	0.35	0.42	0.50	0.55	0.60	0.62

After this study, it is self-evident that the materials studied until now do not cover all the desired range. For this reason, from the simulation results a linear regression has been performed, trying to predict the necessary mixture ratio to bear the remaining part of the velocity interval, resulting in a predicted 21% to withstand to 1 m/s. A last round of simulations confirms the authors' hypothesis, resulting in a limit velocity of ~0.9 m/s, fairly close to the desired value.

As far as the power delivery and distribution are concerned, a parametric analysis based on a power plant modelisation was performed to identify the optimal nuclear power system design for the lunar outpost, focusing on safety, modular design and minimizing power consumption. The design uses lunar regolith as a natural shield against radiation, as illustrated in the two images: nuclear reactors are assumed to be placed in an excavated hole, exploiting the surrounding regolith to attenuate radiation.

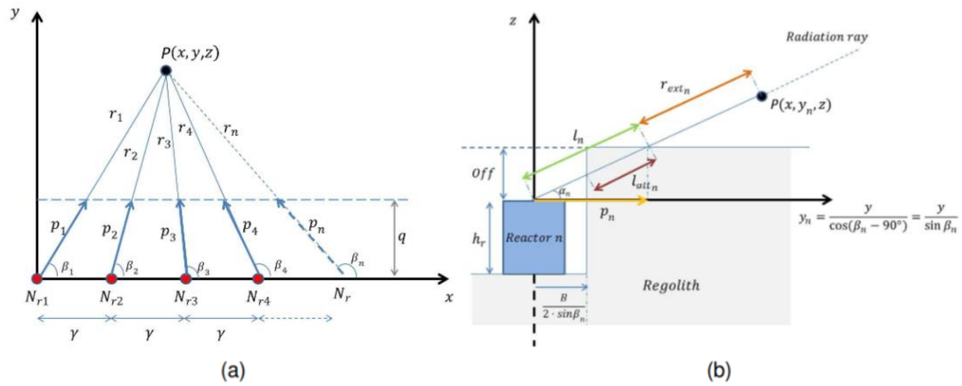


Figure 5: Modelisation of the nuclear plant viewed from above (plane xOy) - (a). Modelisation of the nuclear plant viewed from a side (plane ynOnz). Pay attention to the fact it is the reference Zsystem located in the reactor n, so $y_n \neq y$ axis (b).

Key variables in the model include the number of reactors, inter-reactor distance, hole width, vertical offset, and the location of radiation dose computation. Radiation is assumed to concentrate at the top of each reactor bulk, with regolith fully absorbing it without scattering effect. The goal was to find the optimal combination of these variables to minimize the required safety distance. In fact, if no shield is provided, long distances, in the order of km, must be ensured, with obvious drawbacks, like maintenance issues and heat dispersion.

The best configuration identified includes 5-6 reactors spaced 5 meters apart, with a 50 cm offset and a 3-meter-wide hole, achieving a safety distance of about 90 meters, significantly less than if no shielding were used. The visual outcome of the model shows the reactors, the regolith, and the iso-radiation surfaces at the 5 rem/year health limit, including also cosmic radiation for a realistic assessment, as reported in the figure. Indeed, this model demonstrated that shielding drastically reduces the safety distance and energy losses, with consistent saving on cabling.

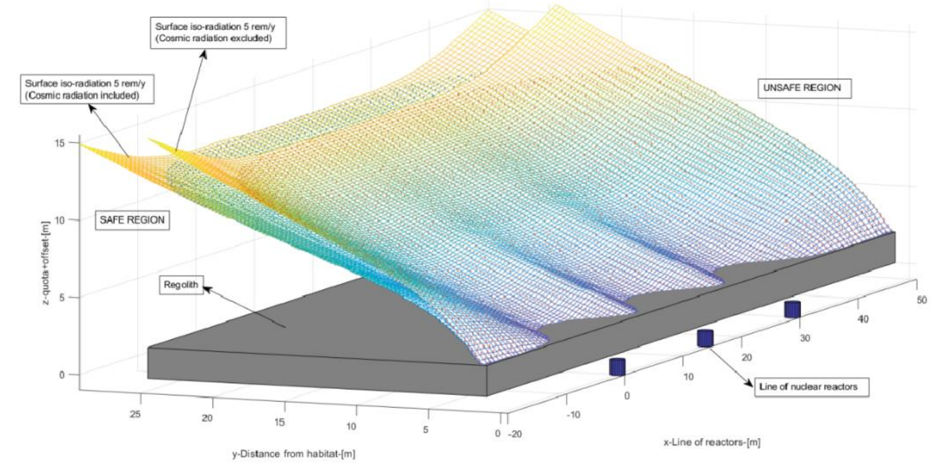


Figure 6: Surfaces iso-radiation resulting from the model.

To conclude, it is paramount to stress that appropriate safety factors could be applied to the value of safety distance obtained, to overcome the simplifications of the model, though they were always assumed through a conservative perspective. What really matters, however, is the overall reduction in terms of distance between settlement and plant in case of shielded plant, permitting to save hundreds of meters of cables and reducing energy dispersion.

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