EURO-CARES Extraterrestrial Sample Curation Facility: Architecture as an enabler of science.

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EURO-CARES (European Curation of Astromaterials Returned from Exploration of Space) is a three year, multinational project, funded under the European Commission's Horizon2020 research program. A multidisciplinary team of experts from academia and industry are developing a roadmap for a European Sample Curation Facility (ESCF). The ESCF is designed to be able to receive mission return capsules, to access the containers held within and the samples, to curate and store the samples, whether they are restricted (Mars, Europa, etc.) or not (Moon, asteroid, etc.). In 2016, Master students of the Vienna University of Technology worked on a proposal for the architectural layout. In 2017, a team from Merrick and Company (Canada) joined the collaboration to create a more technologically-sound design. The project team believes that a tight collaboration between architects and scientists in the early stage of the design operations will allow to increase the functionality of such a building. However, finding a common language and defining clear requirements of what scientists expect and what architects can plan is a challenging task. Current status of the project is presented, as well as selected design proposals for the facility. Requirements and specifications from various perspectives are discussed and the design process is summarized.

Nomenclature

DWI	=	Double-Walled Isolator
ESCF	=	Extra-terrestrial Sample Curation Facility
EURO-CARES	=	European Curation of Astromaterials Returned from Exploration of Space
FU	=	Functional Unit
HEPA	=	High-Efficiency Particulate Air

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PRF	=	Portable Receiving Facility
SCF	=	Sample Curation Facility
SRF	=	Sample Receiving Facility
UP	=	Utility Plant
WP	=	Work Package

I. Introduction

EURO-CARES (European Curation of Astromaterials Returned from Exploration of Space) is a three-year, multinational project, funded by the European Commission's Horizon2020 research program, from January 2015 to December 2017.

At the present time, there is no curatorial facility in Europe like the NASA Johnson Space Center Curation Facility (Houston, USA), or the JAXA curation facility (Sagamihara, Japan), which host samples returned from the Moon and from asteroids. With Mars sample return missions planned for the future, it is imperative to plan a facility to host these potentially-biohazardous samples especially as the design, construction, and certification of such a facility can take a decade to be completed[1]. The objective of the EURO-CARES project is to create a roadmap for the implementation of a european Extra-terrestrial Sample Curation Facility (ESCF), to allow Europe to be fully involved in sample return missions.

COSPAR[2] defines five planetary protection categories with subcategories dependent on the target of the mission and the type of mission (fly-by, orbiter, or lander). Category I missions do not have planetary protection requirements, e.g., for missions to undifferentiated, metamorphosed asteroids or Io. Category V missions include the most stringent planetary protection requirements. All missions which will return extra-terrestrial samples to Earth for further analysis belong to category V. Dependent on the origin of the extra-terrestrial material, a category V mission can be an unrestricted Earth return mission (e.g., with samples from the Moon) or restricted Earth return mission (e.g., with samples from Mars or Europa). There are no special requirements for sample containment for unrestricted missions. However, for restricted missions where there is thought to be a possibility of life to be (or to have been) present, the requirements include: absolute prohibition of destructive impact upon return, containment of all returned hardware which directly contacted the target body, and containment of any unsterilized samples returned to Earth.

In the present work, we use the terms "restricted" and "unrestricted" for the samples themselves. On one hand, the facility should be designed and constructed to prevent sample contamination and alteration, and on the other hand, to prevent potential biohazards from the sample (this second point applies only in case of restricted samples).

There have been a few previous studies on curation facilities, which have been typically either country-specific[3] or mission/target specific (e.g., for Marco Polo-R[4]). EURO-CARES proposes to move onwards from these specific studies to look at what would need to be done to create a European facility that would be suitable for the curation of samples from all possible return missions likely over the next few decades, to the Moon, asteroids, and Mars.

Study and long-term curation of returned extra-terrestrial samples requires the samples to be kept protected against a range of contaminants which may affect their scientific analysis. For restricted mission samples they will require containment to prevent the release of any biohazards until they can either be shown to be devoid of any life-forms or be effectively sterilised (i.e., to inactivate any life-forms). The co-requirements for a combined high containment and ultraclean facility are unique and thus will lead to the development of a highly specialised facility, that will require the development of novel scientific and engineering techniques.

The EURO-CARES consortium is composed of space scientists, biosafety specialists, curators and engineers. A collaboration with architects and designers was deemed necessary to add technical expertise and to bring different point of views in the project. An architecture design studio[5] was organised in year 2 of the project (2016) between the Austrian team of EURO-CARES and the Vienna University of Technology, involving a number of architecture students. These students were briefed by different branches of the team, each relaying certain aspects and requirements of the facility, focusing on the laboratories.

Operation and sample flows were studied extensively during the workshop. It was stressed that the flow of samples would change for different samples and would require different laboratory environments and different clean paths and cycles. Fourteen facilities were designed. Some designs were more focused on public observation of curation activities while others had different buildings for each function, for easier construction. The collaboration resulted in stronger requirements for the ESCF. Results of the Design Studio[5] were presented during a workshop hosted at the Natural History Museum Vienna in April 2016, to scientists and architects.

In early 2017, a collaboration with the team of Merrick and Company (Canada) took place, with a focus on more technical and engineering aspects of the different laboratories. A student from the 2016 Design Studio was selected (E. Kilic) to take part in this phase, as training of young professionals is deemed important for such long terms projects. Two weeks of intensive collaboration resulted in the development of a number of different layouts for the laboratories (see Appendices A, B and C). The constant dialogue between engineers, architects, and scientists helped constrain stronger requirements for the laboratories as well as for the whole site.

We present here the EURO-CARES project in more details and the expected scientific procedures in the ESCF. We then define the technical and architectural requirements, and show some interpretations of these requirements.

II. EURO-CARES

EURO-CARES team work is organized around five distinct technical Work Packages (WP) described below[6] (www.euro-cares.eu), led by curators, scientists and engineers from all over Europe. Along with the scientific and technical requirements, EURO-CARES project is also focused on a high impact public engagement plan (WP8) that engages children, university students, the general public and policy makers, as well as our academic and industrial peers.

A. WP2: Planetary protection

It will be necessary to address the risks involved in handling possibly biogenic material and to examine how we can mitigate them, whether it is through adapting the design of the building or the protocols[7]. This will require a specific biohazard assessment protocol to determine the potential threat to the terrestrial biosphere prior to release the samples from containment for investigation by the wider scientific community. Planetary protection requirements and implementation approaches are determined by the best multidisciplinary scientific advice[8] according to international policy and recent recommendations from the European Science Foundation.

B. WP3: Facilities and infrastructure

The objective of this work package is to define the state of the art facilities required to receive, contain and curate extra-terrestrial samples and guarantee terrestrial planetary protection. All the aspects, from the building design to the storage of the samples as well as the curation are covered by this work package. The curation facility primary goal is to enable long-term, high quality research, either by providing pristine samples to the science community, or by planning fully functional laboratories within the facility, while (in the case of restricted samples) ensuring that all the planetary protection requirements are fulfilled to prevent a release of potential biologically active contamination into the ambient environment. All the specificities of the samples, including their origin, if from Mars, the Moon, and/or from asteroids, their size, their form, etc., are considered in this activity.

Storage of the samples: Long-term curation of samples is challenging, especially because their pristine nature should be preserved as much as possible, knowing that in case of biohazardous samples some specific planetary protection constraints will have to be undertaken. The facility will have to operate at controlled pressure, temperature, and atmospheric environment, depending on the samples requirements. Contamination should also be monitored with specific witness materials to be already placed inside the sample catcher/container on the spacecraft.

Curation: It mainly consists of the handling, documentation, preparation, preservation and allocation of limited amount of sample for research. Curators should already be consulted during the mission design, not only as expert of the samples to be collected, but also to be able to help in designing the sampling devices and to ensure proper monitoring of the contamination. Each of the collected and curated samples have a unique history and come from different environments, therefore, the different types of samples present specific and unique challenges for appropriate curation and to insure their integrity. Different documentation, handling, and preparation technologies were designed, developed, and tested in the last decades but still some issues remain to be further investigated; a specific challenge is the manipulation of small samples (micrometer-sized).

C. WP4: Instruments and methods

The objective of this work package is to determine which analyses should be performed within the ESCF while ensuring minimal contamination and minimal damage to the sample. The definition of the boundary between "curation" and "science" will define which instruments and protocols should be used, and hence, the design of the laboratories. Another goal is to ensure contamination control through use of innovative methods and high-level contamination mitigation and identification protocols.

D. WP5: Analogue samples

Analogue proxies are necessary in a curatorial facility for testing sample handling, storage and preparation techniques, and to train workers. For practical reasons, it seems necessary for the curation and analytical facilities to have their own collection of analogue samples.

E. WP6: Portable receiving technologies

The objective of this work package is to propose methods for the recovery and transport of samples from the landing site to the permanent curatorial facility. These methods are of the utmost importance to break the chain of contact between Earth and extra-terrestrial matter. Once the Earth return capsule has landed, an assessment of the state of the spacecraft will lead to a recommended recovery procedure. A portable receiving facility may be used to inspect, document and package the sample container(s). The container will then be transported to the permanent curatorial facility using a safe and secure method. In addition, methods for the transport of samples from the facility to the outside institutions have been studied, to ensure security and non-contamination of the samples.

III. Science program

Curation in the facility has two main goals: first, conducting basic analyses on the samples and associated hardware; Second, curating sensu stricto, i.e., storing, handling and managing the samples as a valuable scientific resource for generations of researchers to study. The first goal is the phase of Sample Early Characterisation (SEC). This phase aims at characterising the samples with non-destructive methods to set the basics for high-quality research to be done afterwards. The next step is the Preliminary Examination (PE) phase, in which further analyses are conducted on the samples (figure 1). Depending on the nature of the samples, this phase can be done inside or outside of the ESCF. It is planned to keep the curation facility as light as possible regarding instrumentation, and to distribute the samples to external laboratories for unrestricted samples, or for restricted samples in special sealed containers. However, in the case of restricted samples, it will be necessary to keep most of the research under containment. Some part of the sample will need to be devoted to Life Detection (LD) and Biohazard Assessment Protocols (BAP)[9], with analyses encompassing non-destructive, destructive, microbiology cultures, and potentially animal tissue testing.

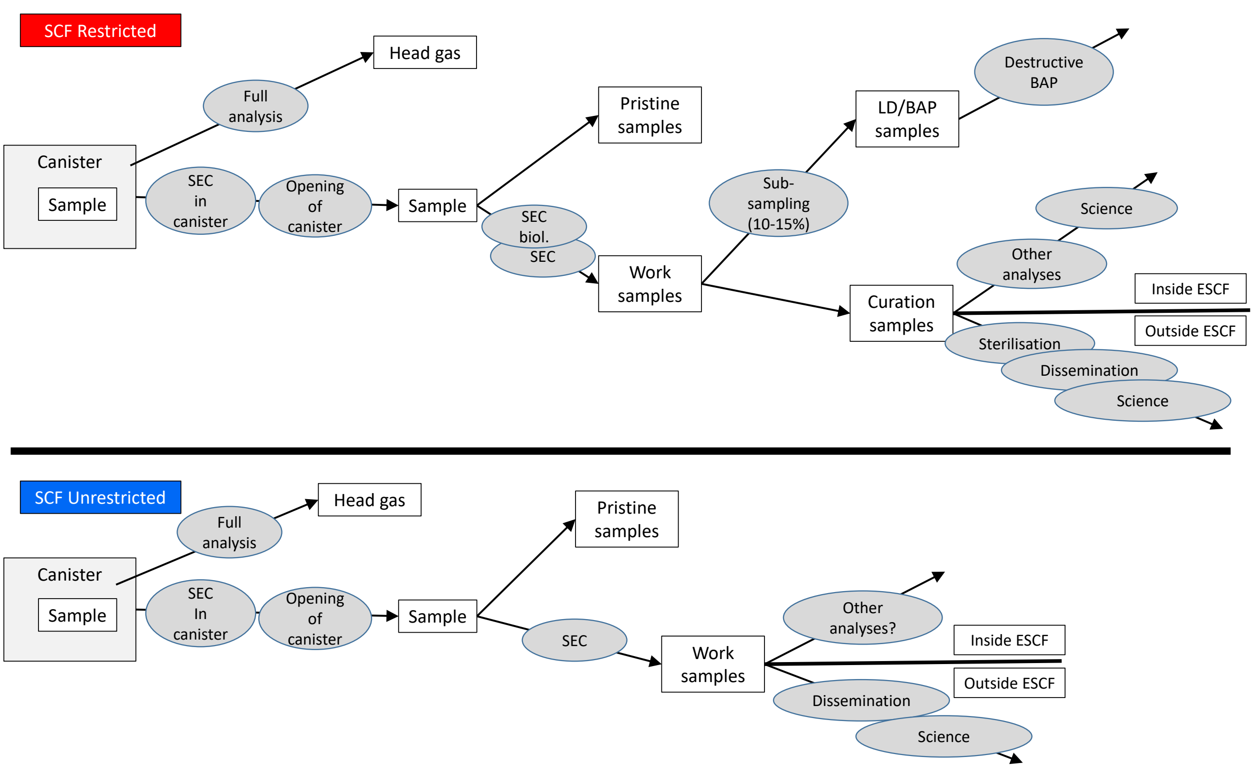


Figure 1. Restricted versus unrestricted samples spliting alongside the procedures, in SCFs.

During sample receiving and SEC/PE, there is a close connection between the needs of the scientific investigations and those of the curation and management of the samples. Given that it will likely be that the exact nature of the samples will be uncertain, e.g., if a core sample has remained intact or whether frozen samples have remained frozen, it is critical that a high-degree of flexibility in terms of both technology and personnel training is factored in.

IV. Technical requirements

The design requirements used here were derived not only from discussions within the EURO-CARES consortium but are also based on scientific requirements and on a study of the evolution of similar facilities (i.e., in terms of complexity) all over the world.

A. Design requirements

For restricted samples, the facility should be designed so that an unsterilized particle >0.1µm should have a probability $P<1x10^{-6}$ of release[10].

Samples should be kept protected from contamination, whether the contamination is organic, particulate or biological. The ISO standard for cleanrooms should be used, with cleanrooms from ISO 6 to 4.

Several locations could be envisioned for the ESCF, such as a "remote location" (i.e., relatively far from an inhabited area), an existing university or research centre, an existing governmental (or non-governmental) facility, etc. Not having constraints on this aspect, we made the assumption that the ESCF is a stand-alone facility which does not use any remodelled building(s).

The architectural layout shall encourage meetings and communication between personnel to increase working efficiency and cooperation.

The architectural layout shall encourage the health and wellbeing of staff by providing a pleasant work environment. This aspect has been rarely considered in similar facilities (NASA JSC and JAXA). Since cleanroom workers show significantly higher sick leave statistics[11] than other personnel, this requirement should not be overlooked.

Security should be layered according to risk associated with samples/personnel/building in general.

Scientific units should be protected from a range of natural (such as seismic hazard) and non-natural hazards.

As stated clearly in the proposal, the ESCF should be built in Europe. European and local (when a country is chosen) legislation should then prevail for the design and building.

The human/restricted samples interaction should be minimized, for safety and security reasons.

Additionally, the facility shall be designed to avoid unnecessary resource or energy use, both in the building and operational phase (material selection, energy efficiency, etc.). The facility shall be cost-effective by considering the whole life cycle, including the initial design and construction costs, operations, and maintenance as well as disposal.

In practice, for restricted return missions, the first requirement has been that any samples should be housed in a high-containment facility. BSL-4 facilities[7] are used to handle the most dangerous micro-organisms, those with a high case fatality rate and a lack of effective vaccine or therapeutics such as Ebola virus. Such facilities are available in a few European countries including France, Germany, Sweden, Switzerland, and the UK. They are constructed using two basic designs, either cabinet line or suited laboratory. In the cabinet line facility all samples are handled in linked glove-boxes (Class III microbiological safety cabinets), while in a suited laboratory they are handled in Class II safety cabinets by operators in positive pressure suits fed with breathing air. These facilities are kept at negative pressure to their exterior and all exhaust air is double HEPA (High-Efficiency Particulate Air) filtered. All waste is autoclaved, or heat or chemical treated by validated means. Such facilities have very high operating costs and much of the facility must be given over to engineering services (HVAC, effluent treatment, etc.). Since these facilities are not in any way designed and constructed to protect samples from terrestrial contamination and often require turbulent airflows they cannot be used to handle extraterrestrial samples as they would contaminate them. Therefore, any restricted ECSF must incorporate the general principles of BSL-4 containment but not completely replicate them, hence be a hybrid of a BSL-4 laboratory[12].

Adequate space for mechanical, electrical and plumbing services should be planned in the design, to ensure that maintenance and operation of the equipment are state-of-the-art.

All these above-mentioned requirements were interpreted according to scientific requirements obtained from the others WPs, and according to technical and architectural feasibility; The results are shown in the next sections.

B. Functional Units of the ESCF

The EURO-CARES WP3 team has broken down the activities of the ESCF to define independent functional units (FU) (table 1), each one serving a distinct purpose (curation, work support, public outreach, etc.) which allows a flexibility in design.

Portable Receiving Facility (PRF) is not to be considered in the ESCF building design. Remote Storage is neither physically linked to the ESCF and is not discussed in the present article. All the other FUs, Sample Receiving Facility (SRF), Sample Curation Facility (SCF), Analogue/Mock-Up Facility (AMUF), Work Space, and Public Outreach are units to be co-located on a single campus.

Each FU has been broken into sub-functional units, according to the tasks to be accomplished (figure 2). This figure is showing only scientific tasks, and do not show the necessary equipment or structures necessary to fulfill them (e.g., changing rooms, autoclaves, etc.). These were defined afterwards, with the input of engineers and architects.

Table 1. Functional Units of the ESCF. *The color red is used for scientific FUs dealing with potentially biohazardous samples. The color blue is used for scientific FUs dealing with unrestricted samples. The color yellow is used for the last scientific FU, which will host only terrestrial samples. The color green is used for accommodation of people.*

PRF Restricted	PRF Unrestricted	Assessing, cleaning and packaging the spacecraft on the landing site. Delivery of the spacecraft to SRF.
SRF Restricted	SRF Unrestricted	Receiving the sample container, cleaning and opening of the outer layers and delivery of the unopened sample canisters to the curation facility. Clean environment (ISO 7 to 5). For restricted samples, containment environment.
SCF Restricted	SCF Unrestricted	Receiving of the sample canister, accessing the samples. Preliminary Examination (sample and hardware) and Sample Early Characterisation, Curation and Dissemination. For restricted samples, Life Detection and Biohazard Assessment Protocol. Ultra-clean environment (ISO 5-4). For restricted samples, high containment environment.
Work Space		Support space for workers (offices, meeting rooms, social rooms, restaurant, etc.).
Public Outreach		Space accessible to the public (different categories of public, TBD) to promote the activities of the ESCF.
Analogue/Mock-Up facility		Personnel training, instruments and protocols testing on analogue samples. Material testing for cleanliness and containment suitability.
Remote Storage Unrestricted	Remote Storage Restricted	Storage under dead-mode of a TBD part of the samples. Clean environment. For restricted samples, containment environment.

V. Design approach

A. Design for flexibility

Flexibility is seen as one of the most important concepts to be considered for such a project to allow for the future development of scientific analytical capabilities, and to adapt for the lack of concrete building plan and defined site. This concept has been developed at several scales, with the requirement of future extensions and potential growth. Each core function of the ESCF is linked to a Functional Unit (FU).

- "Campus" scale: units should be linked in a way that allows efficient flows of persons and materials. Any meaningful combination of units, at any time, should make sense structurally, technically and architecturally. This flexibility is important as long as the funding and building status is not better defined, to allow for different possible scenarios. It can also be a way to (quickly) adapt to a change of mission politics, or to the failure of a mission.
- "Functional unit" scale: one unit should be easily adaptable for future developments and expansion of activities and utilities (mechanical, electrical, etc.). In most of the similar facilities (such as at NASA JSC and JAXA), non-scientific rooms (usually work spaces or public outreach spaces) are retrofitted after some time to accommodate new missions or science goals. It usually results in laboratories not as much functional as if they would have been planned from the beginning, and it also reduces the well-being of workers.

- “Room” scale: some rooms should allow for restructuration or change of the activity to be conducted inside. It should be stated here that a given laboratory will need to be completed years before the return of the samples. Consequently, without knowledge of the exact nature of the samples or of the condition of the sample inside the containers (see NASA's Genesis sample-return mission[13]), the laboratory should be easily adaptable (i.e., by adding new instruments that were not forth planned for example).

Planning for changes is critical to ensure functional goals can evolve as time progresses. Design for flexibility can be thought of:

- Phasing of functional units
- Design of support services to accommodate growth or changes
- Design for re-sizing of rooms and internal areas
- Design for expansion of proposed buildings

ESCF planning has factored each of the flexible design goals by developing plans that can accommodate phasing of building units using relationship planning factoring shared elements and services extension(s). Using basic processes factoring the flow of people, samples, waste, and supplies linked with security layers and cleanliness/containment principles, initial designs have accommodated the growth of a site to accommodate additional functional units.

Design flexibility should also accommodate various requirements for environmental changes and growth of interior functional zones. The ESCF requires critical systems to adjust and change as needs change for the curation of the samples starting with protection of the environment, followed by the protection of the samples. Thus, the design for flexibility needs to accommodate both, change in environmental parameters and also expansion of the services and potentially changes in regulations and guidance.

Rooms are typically designed with four walls, ceilings, and floors that are, in many contained or high security facilities, made of robust materials such as concrete to allow pressure testing and special coating liners capability for decontamination, creating rigidity, and inflexible space for future changes. The current ESCF planning process is challenging these paradigms by investigating alternative materials such as polymer panel systems, adjustable wall framing, synchronized placement services for environmental parameters, and re-use of materials during changes.

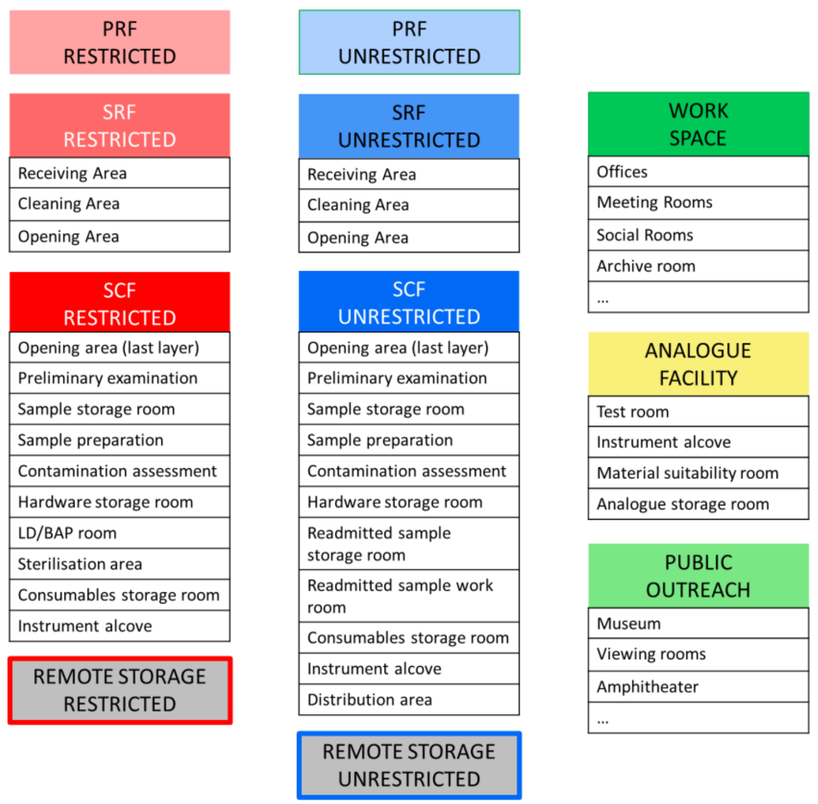


Figure 2. Sub-functional units. *Each sub-unit serves a specific (scientific) purpose.*

Design flexibility for expansion while stated as a goal in basic design planning rarely sees a reality factoring a need for building expansion. The ESCF is planning for expansion using several design approaches. First, buildings are being planned to accommodate change of their technical systems to increase needs for expanding buildings. Second, the building design zones and their use of buffer corridors permits future lateral expansion with minimal impact to current operations. Lastly, services can be sized from a site perspective to accommodate increased growth and new area requirements.

Flexibility as a design parameter can be subjective without quantifiable goals or fixed targets. While architect/engineer designers typically request numbers for planning growth or frequency of change of existing space, the ESCF initial planning objectives are broad to accommodate variations in sites, phasing of functional building units, materials designed for changes, systems design for expansions, and additions and layouts that can accommodate lateral expansions. In a project like the one presented here, design for flexibility must be a forethought, not an afterthought.

Importantly, we do not consider any retrofitting of a specific unit to perform another use, since it is prohibitive both for time and in term of cost[14].

B. Design for security

Requirements state that the ESCF should be able to withstand a variety of natural and non-natural threats. Although these risks will be better defined when a site will be chosen, the arrangement of the FUs can already provide some answers, especially to mitigate potential terrorist attacks.

Security as a whole is usually provided by adding layers of increasing security (those layers can be both physical (addition of gates/barriers) and administrative (restricted accesses)).

An option would be to place scientific FUs (table 1, figure 2), especially for restricted samples, under the other FUs, the latter acting as a shell. An illustration of this principle is the design "Introvert" from the Design Studio (2016), presented in figure 3.

C. Functional layout for scientific FUs

Each sub-functional units were quantified in term of their size. Inputs from WP4 "Instruments and methods" led to completely separate the FUs for restricted and unrestricted samples, since instruments cannot be shared. Although SRF and SCF do not have to be physically close by, we decided to keep them close to each other to allow a smooth integration of the Earth-Return Capsule (ERC) from the SRF to the SCF. With the inputs of WP5 "Analogue samples" and the recommendations of the engineers and architects to include a material testing space, we designed the AMUF layout.

Figure 3. Introvert. *In this design, the most sensitive areas are surrounded by the other FUs, to ensure maximal security. Design of Julius Heffner*[5]

The first step was to define the functional relationships, and adjacency of each room or area of the FUs. To do so, the environment of each room, in term of cleanliness, containment levels (for restricted samples), presence of humans and/or robots, etc., was defined. Samples, staff, and process flows were mapped and taken into account in the design.

The layouts presented in appendix show only one level, the laboratory itself. Other levels are necessary for mechanical, electrical, filters and plumbing services, with a height sufficient enough for an easy maintenance (appendix A).

1. *Analogue / Mock-Up Facility*

This functional unit is planned to be built before all the other scientific FUs, and has several purposes:

- testing of materials and building techniques, before applying those to the other scientific FUs;
- testing of protocols and instruments, by using analogue samples;
- storing a sufficient collection of analogue samples;
- training of staff for clean room and containment practices;
- participating to the public outreach program.

We designed this FU to be rather small (compared to the other FUs), as a "sandbox" allowing curators, researchers, engineers, technicians, and even contractors to test and validate the protocols and materials before using them in real conditions on the precious returned samples. The AMUF is composed of a full shower suit suite (replica from the one to be used to enter restricted FUs), a "villi system" (figure 4), a storage room, a replica of an examination room, and a smaller room to be used for material testing (appendix B).

The AMUF will not receive any ERC, so no high-ceiling docking station was included in the design.

2. *Returned sample laboratories: general design decisions*

Restricted and unrestricted FUs were treated separately, for the following main reasons:

- Non-sharing of instruments for restricted and unrestricted samples[15].

- Retrofitting not sustainable[14].
- Containment laboratories are very expensive, better to keep them as small as possible.

For both unrestricted and restricted FUs, we joined SRF and SCF in the functional layout. It is not a strong requirement, but it makes the transfer and opening of the sample canisters easier.

At the interface of SRF and SCF, we included a Material Airlock coupled with a Dirty Tool room. These rooms are used as an airlock on entrance of the ERC/Sample canister, or during the life of the facility, to bring instruments and tools needing maintenance that would disturb the operation of the facility or the cleanliness and containment conditions if done directly inside of the laboratory. A last use for these rooms is to take out decommissioned instruments. For that reason, the Dirty Tool room is accessible from any part of the laboratory, using corridors.

The vault is adjacent to the Preliminary Examination Room so the samples can be accessed and stored right away.

Doors for entering rooms are scaled for either people (single door) or instruments (double doors). In general, doors open contrary to the air flow, so that they will shut down automatically. Sets of two interlocked doors are placed in strategic location, to increase security and cleanliness.

Corridors have been used extensively, to accommodate flows of samples, materials, and workers in between rooms, and to act as a buffer between areas of different cleanliness levels, or of different containment levels.

3. Receiving facility

Receiving facilities (Unrestricted and Restricted SRF) are composed of a high-bay, able to accommodate a truck and potentially cranes if the ERC is too heavy to be moved "manually". A fully enclosed unloading dock is recommended as part of the SRF for cleanliness/containment and for security reasons.

The unloading process, and opening of external layers is considered to be with mostly human operators, even for a restricted sample return (although in that case, positive pressure suits should be used), considering the need of flexibility and adaptability to different types of ERCs, and to unknown condition within each layer of the ERC.

The ERC goes through a cleaning and opening room, and then the sample canister is introduced in the SCF. Layers of the ERC are also introduced in the SCF, to be curated in a dedicated storage room (appendix C and D).

Condition of cleanliness and containment, as well as transfer mechanisms from one room to the other are dependent on whether the samples are restricted or not. Cleanliness and containment requirements will increase as the layers surrounding the returned samples are removed to get to the extra-terrestrial material.

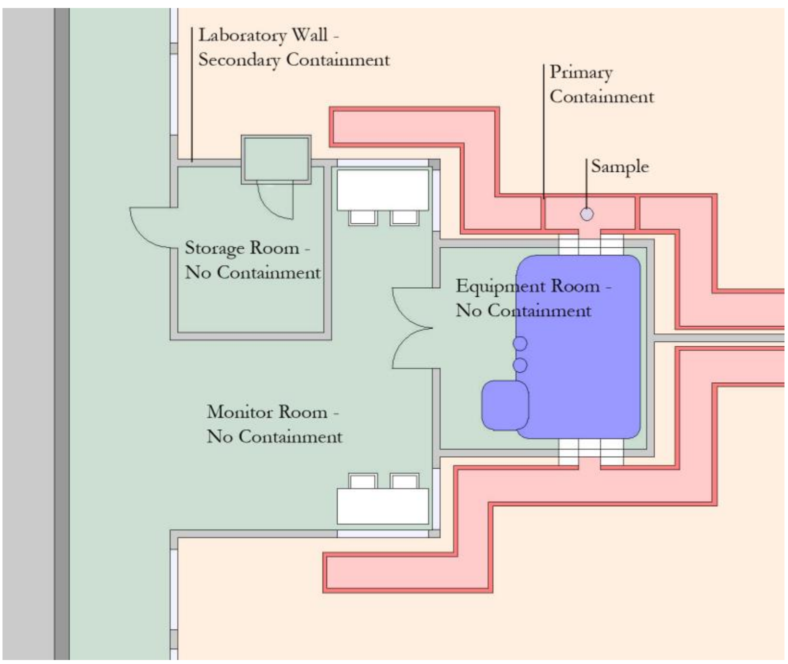


Figure 4. Graphic representation of one villus. *A villus is composed of a non-contained working room (in green), hosting an instrument (in blue). Samples are kept within the primary containment layer (in red), with secondary containment being the laboratory room (in orange).*

4. Analytical facility "Villi"

For the SCF part of the functional layout, we followed recommendations[15] of the WP4 "Instrumentation and methods" in trying to keep the largest instruments outside of the cleanrooms and/or contained areas. This system, based on intertwining contained/clean areas and non-contained ones, was nicknamed "villi" (figure 4), and is detailed below.

The purpose of keeping instruments outside of the working areas is manifold:

- Minimize particles-emitting sources inside the cleanrooms.
- Limit the need to decontaminate (fragile) instruments (for restricted samples).
- Allow staff to operate some of the instruments without going through gowning procedures, and to work in a more relaxed environment.

- Allow maintenance from outside (without disturbing the entire laboratory).

Such a system requires to develop through barrier technologies, such as what is used in Fort Detrick (Maryland, USA, see figure 5).

Each instrument room can be equipped to handle special requirements, such as low vibrations, or magnetic field suppression, etc. The limited size of the room is then an asset to achieve these requirements at low costs, and with known technologies.

"Villi" concept also creates more surface area between contained and noncontained areas. This increased surface area provides flexibility as technology of analytical equipment changes and/or is presently unknown.

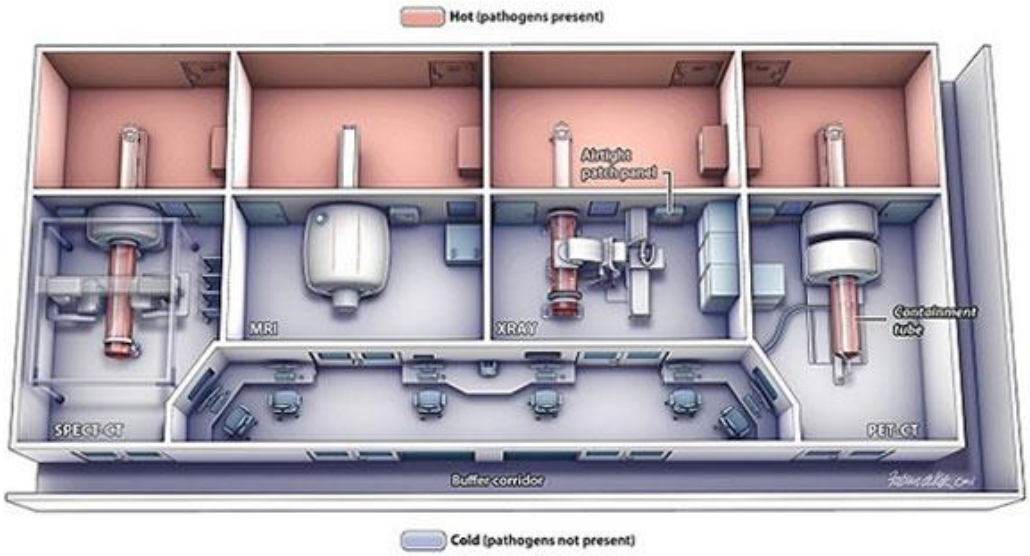


Figure 5. Schematic of the imaging suite at the NIAID Integrated Research Facility[16]

5. *Unrestricted laboratory functional layout*

The Unrestricted SCF is split into one extremely clean part, for pristine and work samples, and a less clean part appendix C), for returned samples, spare hardware storage, and packaging of samples to be disseminated to external laboratories.

Work on samples should be conducted in positive-pressure gloveboxes filled with an inert gas[17, 18]. Staff entrance is possible through a gowning suite adapted to the level of cleanliness.

The receiving area for samples is shared with the general receiving area (for instruments, consumables, maintenance needs, etc.).

Flow of samples and staff is usually through doors, with the occasional use of an air shower, to help maintain the required cleanroom ISO level(s).

6. *Restricted laboratory functional layout*

In this laboratory, the main design driver was the way the samples are handled. At this stage of the project, in the absence of a clear current protocol for SEC/PE and LD/BAP, we chose to use a few different approaches. The biggest part of the facility, thought for SEC and PE, is designed to host a train of Double-Walled Isolators (DWI). A DWI is composed of a negative enclosure (where samples are handled) surrounded by a positive pressure area filled with clean gas[19]. Since a DWI is the primary and secondary barrier, staff can access the laboratory without a positive pressure suit, using only a gowning suit. Staff will be anyhow limited around the DWI because of the fully robotic manipulation inside of the DWI. However, we plan (for emergency procedures, or special maintenance operations) to have a suit suite, but using suits with an independent air intake.

Another part of the facility, thought for the receiving of the sample capsule, and for the LD/BAP, is designed to use either gloveboxes as primary containment, or a full positive pressure suit. Staff entrance for this part is through a suit suite, whether using a suit or not (appendix D).

A material airlock with decontamination capacities between those two parts allows for flows of instruments and staff if needed. This airlock, by isolating completely both parts of the laboratory, allows for a complete shut-down of one part (for maintenance, or in case of emergency) without impacting the other part.

All functional layouts have been tested for flows of workers, samples, material, and waste.

D. Site plan

Although the site is unknown at the moment, we are proposing different possible approaches for building the entire ESCF to fulfil the “Campus” scale flexibility requirement over time.

These approaches are all generated over a unique site, however, the entire concept is made so that if one FU is not built, it does not affect the other ones. Each different approach is presented with a conceptual diagram.

To accommodate such a complex, it is necessary to plan a dedicated Utility Plant (UP), providing power, water, steam, and anything necessary to the operation of the FUs. In emergency cases, single functions should be able to work on their own. It is also imperative to allow certain shut down protocols to be effective in certain time frames. The UP is not included in the conceptual site planning below, for clarity reasons.

Orientation to the surroundings is also important to connect the functions to each other and to the outside world, be it roads for transportation or blocked directions for security reasons. The terrain itself and the degree of elevation and slope might require some changes depending of the design. We do not consider here the physical link between the ESCF and the outside world (roads, etc.).

The relationships between FUs are defined (table 2), in term of circulation of staff.

Table 2. Links matrix for onsite FUs. Physical links to allow for transfer of personnel were taken into account. + indicates a necessary link; - indicates a necessary absence of link; * indicates a possible link, if it is deemed beneficial for scientific goals; no marker indicates that the presence or absence of link is scenario dependent, or left to the discretion of architects.

FUs	SRF Restricted	SCF Restricted	SRF Unrestricted	SCF Unrestricted	Work Space	Public Outreach	AMUF
SRF Restricted							
SCF Restricted	+						
SRF Unrestricted	*	-					
SCF Unrestricted	-	-	+				
Work Space	+	+	+	+			
Public Outreach							
AMUF					+	+	

With the requirements for site flexibility, and with the limitations from the three layouts presented in Appendices A, B and C (position of entrance for trucks and workers, size, etc.), some possibility for site planning is proposed. Each variation is described according to its pros and cons, and a trade off is presented in table 3.

1. *Approach 1 - Unique building*

The functions are stacked on top of each other in a very classical way and hidden under a regular facade.

This method does not allow any easy expansion and the entire complex should be planned at once. This might allow, however, for certain plumbing and effluent systems to be shared, hence reducing the total costs. Outer walls are kept to a minimum, reducing the costs as well. Scientific FUs are better protected from outer threats.

Public and office spaces are close and allow for visitors to have a very close view at the researcher’s activities, which may be good for the complex if a public outreach program is a heavy focus point.

2. *Approach 2 – Puzzle*

Functions are partially separated and one FU (in this instance the work space for the staff) connects the separated functions with each other. The shape this central FU can take is highly flexible.

Flexibility and adaptability are high, for the entire complex, as well as for each FU, with a number of outward and vertical expansion possibilities.

Scientific FUs can be placed away from the entrance of the site (for example to lower the risk of terrorist attacks). Because of the expanse of external walls, the building costs will be higher.

3. *Approach 3 – Bridges*

The functions are independent blocks that are positioned in a way that they allow future expansions.

Connections for staff circulation between the different buildings are through bridges. This configuration allows for great independence of each unit but puts them farther away from each other which results in greater distance for the staff. The cost of such a configuration would be relatively higher than for the other approaches as each consideration regarding the utility would be applied to every single unit.

This approach has the advantage to be highly flexible and great for modular design for a gradually built complex.

4. *Approach 4 - Docking station*

In this configuration the work space overhangs the other FUs. This allows for researcher flow to be seamless from office space to laboratory area while allowing expansion to the sides. Outer side of the labs are reserved for the transportation purposes. Please note that on the diagram that the functions not only border each other but intersect, unlike in the "Unique building" approach.

This particular configuration offers great versatility while being compact on the laboratory side.

The laboratories are partially exposed (to aerial threats), but the more restricted parts could be flipped to the side where they are merging with the office portion, to offer an extra level of security concerning non-natural threats.

5. *Approach 5 - Shell*

Each function is laid on the site and a shell is wrapped around the FUs. Functions are placed far from each other so they can be expanded as needed in the future. This configuration offers the most versatility as the shell protects the whole complex despite everything being separated. Moreover, a shell is acting as an extra buffer to keep pressure cascade in laboratories.

The downside of this approach would be the initial cost and estimation of the covered site portion with the shell. A certain margin would have to be calculated and the blocks would be placed giving them enough room to expand in future. Shell could be either covering the whole campus (Shell 1) or in between FUs (Shell 2).

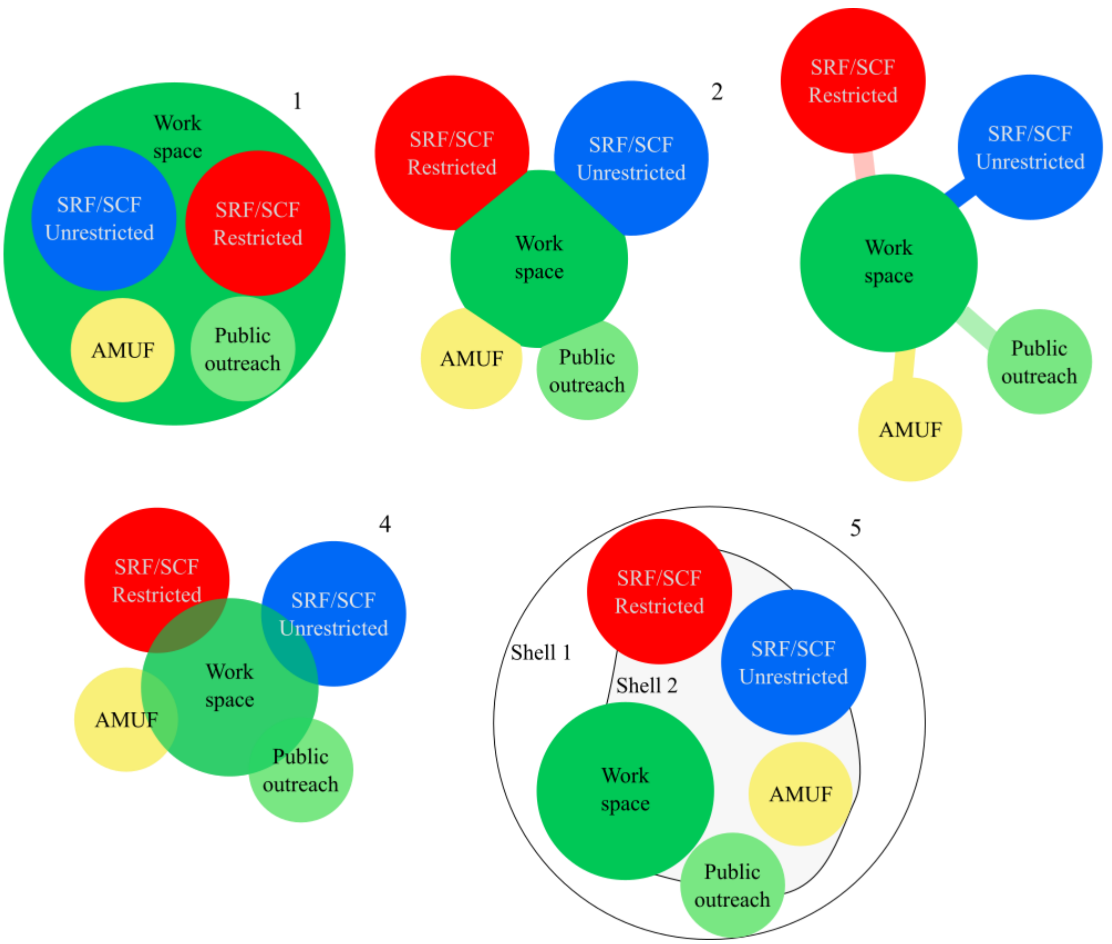


Figure 6. Design approaches for all onsite FUs.

Table 3. Trade-off between the different siting approaches. *"+" indicates that the approach ranks positively for the criterion, "=" indicates that the approach is neutral, and "-" indicates that the approach is at a disadvantage for the criterion.*				
Approach	"Campus" Flexibility	Security	Economics	"FU" Flexibility
1 - Single building	-	=	+	-
2 - Puzzle	=	-	=	=
3 - Bridges	+	-	=	+
4 - Docking station	=	+	+	=
5 - Shell	+	+	-	+

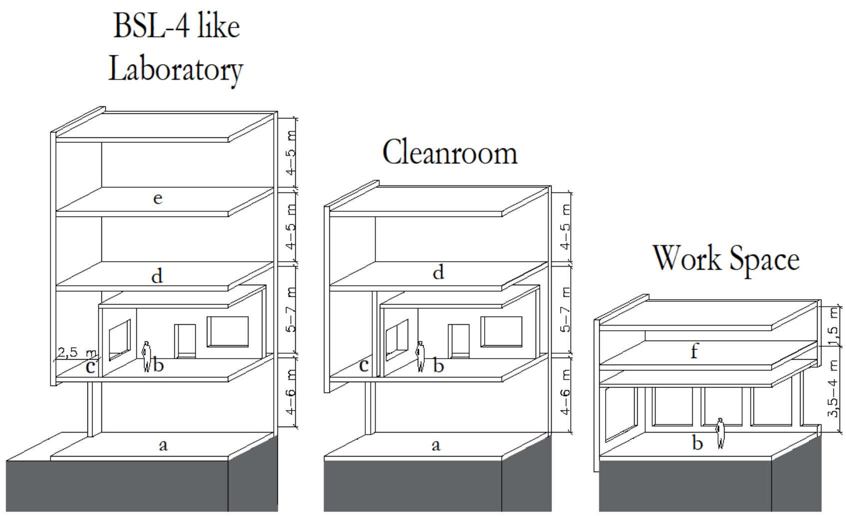
VI. Recommendations and next steps

The collaborations between the EURO-CARES consortium, the Vienna University of Technology, and Merrick and Company brought scientists, engineers, and architects together. This multidisciplinary approach lead to stronger requirements for the ESCF, and to a better understanding of what each side can bring to the others. We strongly suggest that architects should be involved at the very beginning of any project aiming at designing a curation facility for extra-terrestrial samples.

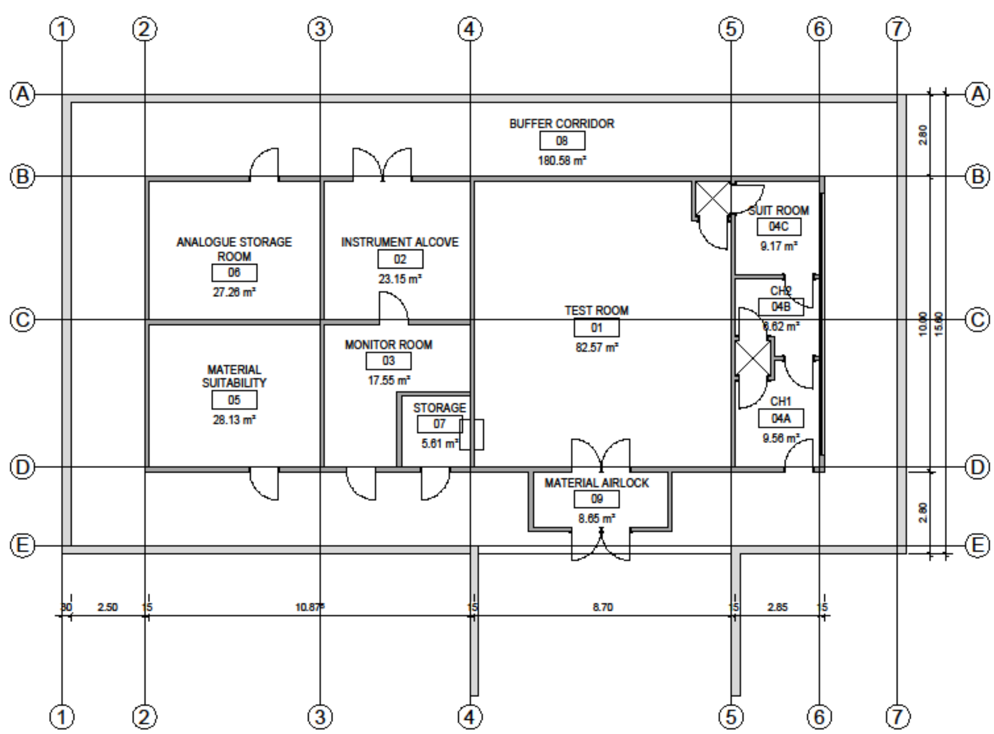
The current study shows theoretical solutions to the technical challenges a facility like the ESCF must face. These solutions can be adapted in the event of a building phase.

The EURO-CARES project is ending in December 2017. The first two years's work has been split between five technical teams. The last 9 months of the project are devoted to an effort of synthesis, and a larger exposure to the scientific and architecture community, to gather feedback and inputs on a more comprehensive project.

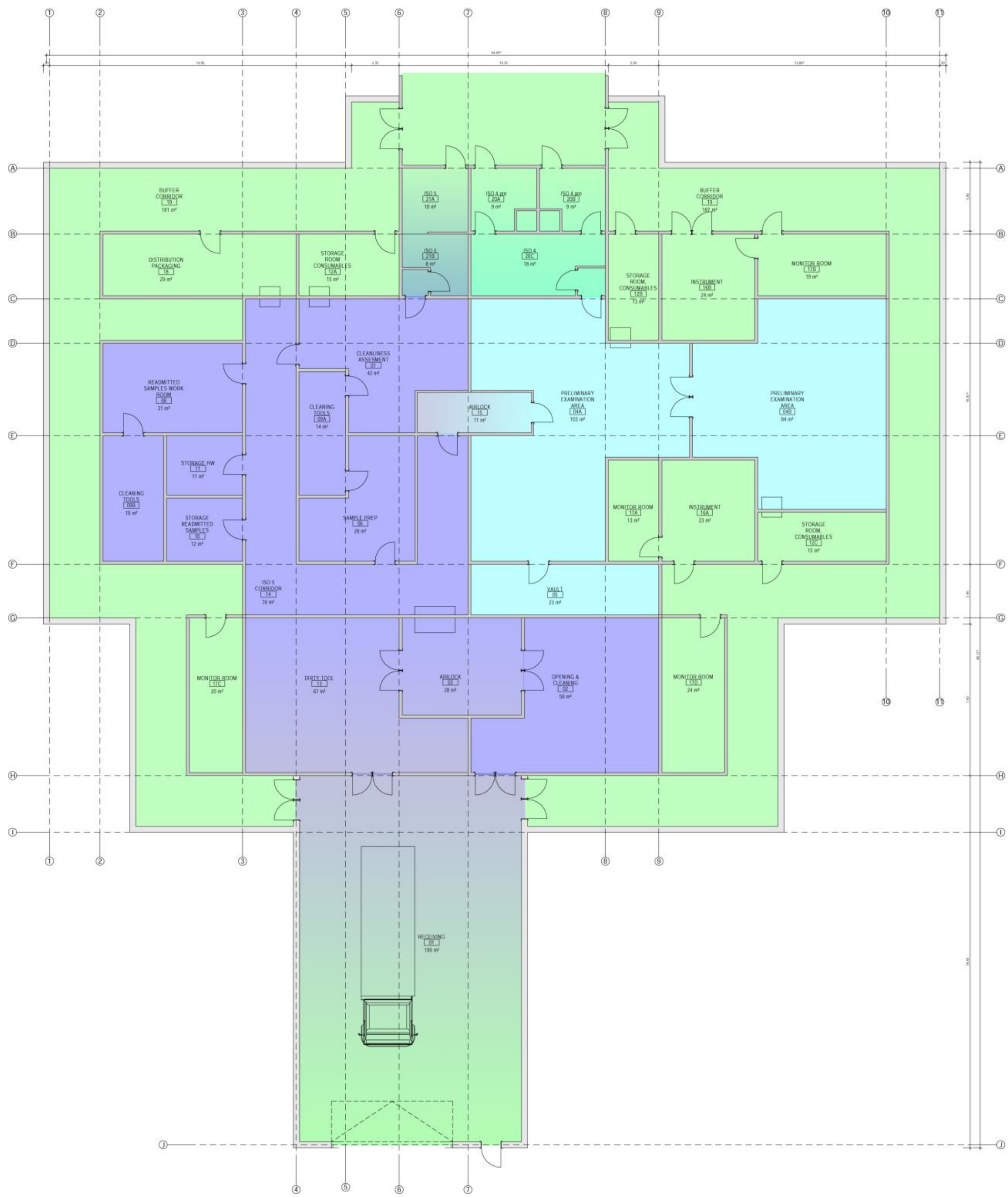
Appendix



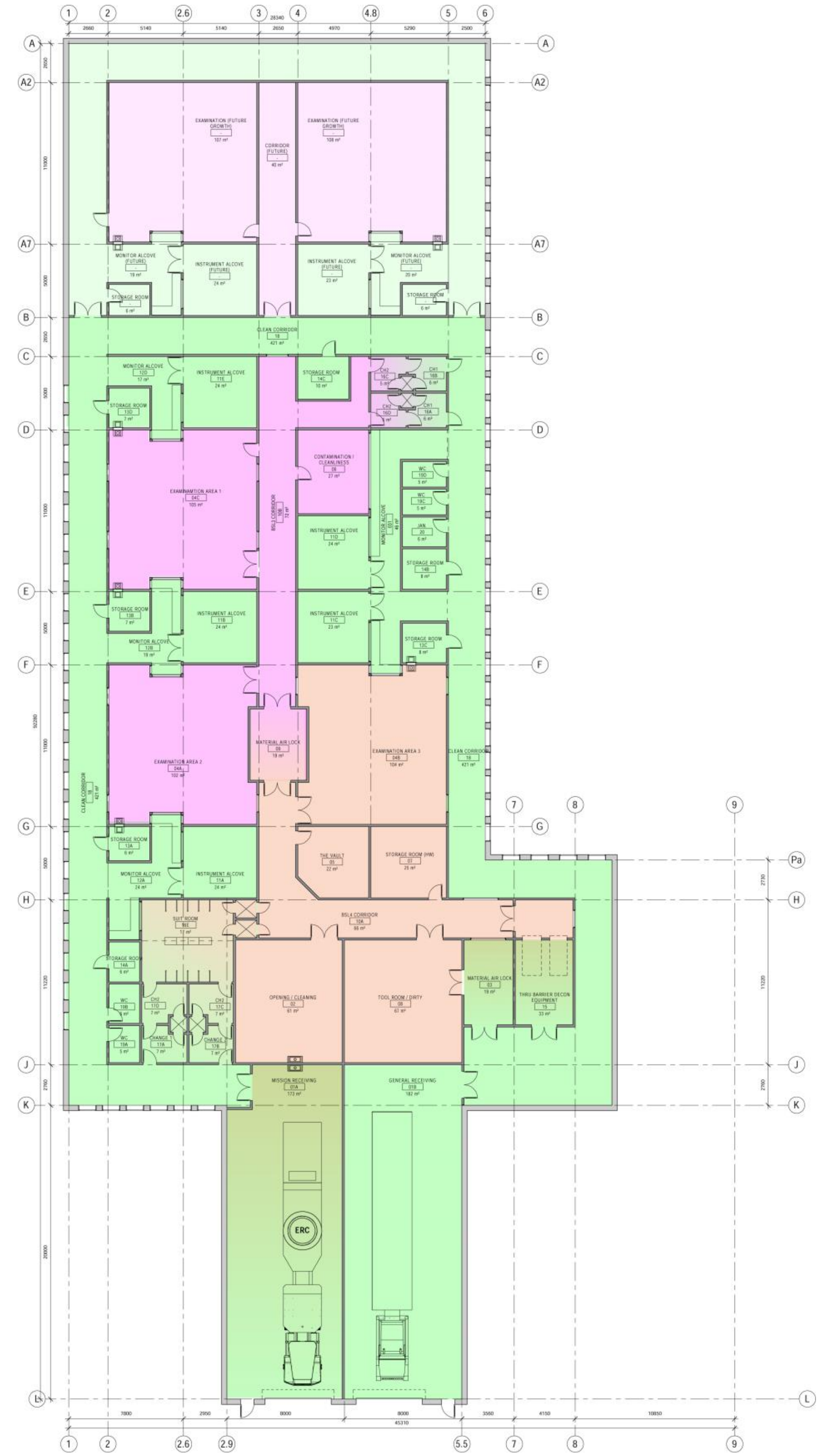
Appendix A. Required heights for FUs. A BSL-4 like laboratory will be used for all restricted FUs. Cleanroom design will be used for all unrestricted FUs. (a) Effluent systems and waste treatment; (b) Working space; (c) Buffer corridor; (d) Air filtering systems I; (e) Air filtering systems II (if necessary); (f) Ventilation systems.



Appendix B. Analogue/Mock-Up Facility functional layout.



Appendix C. Unrestricted SRF and SCF functional layout. *Colours indicate the levels of cleanliness from green (ambient) to light blue (high level of cleanliness).*



Appendix D. Restricted SRF and SCF functional layout. Green indicates areas that are not contained. Pink indicates the contained areas where work is conducted using DWIs or MSC3. Orange indicates areas where a suit is necessary.

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