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A broad introduction to the design and construction of biosafety laboratories in low-resource settings

Enhancement of CBRN capacities of South East Asia in addressing CBRN risk mitigation concerning CBRN first response, biosafety and biosecurity, awareness raising and legal framework

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ACRONYMS AND ABBREVIATIONS

APC	Approved Project Cost
BET	Biorisk Expert Team
BSC	Biological safety cabinets
BSL	BioSafety Level
BSO	Biological Safety Officer
CBRN	Chemical, Biological, Radiological and Nuclear
CCTV	Closed Circuit Television
CoE	Centres of Excellence
DET	Design Expert Team
EDS	Effluent Decontamination Systems
EU	European Union
FF&E	Furniture, Fixtures and non-laboratory Equipment
FIIAPP	Ibero-American Foundation for Administration and Public Policies
GMPP	Good Microbiological Practices and Procedures
HEPA	High Efficiency Particle Air
IHR	International Health Regulations
NIC	National Isolation Centre
NIHE	National Institute of Hygiene and Epidemiology
RITM	Research Institute for Tropical Medicine
SEA	Southeast Asia
UPS	Uninterruptable Power Supply
URS	User's Requirement Specifications
WHO	World Health Organization
WP	Work Package

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PREFACE

This booklet has been produced within the framework of the European Union (EU) Chemical, Biological, Radiological and Nuclear Centres of Excellence Risk Mitigation Initiative (CBRN CoE) Project 46 'Enhancement of CBRN capacities of South East Asia in addressing CBRN risk mitigation concerning CBRN first response, biosafety and biosecurity, awareness raising and legal framework'.

EU CBRN CoE Project 46 aims at enhancing CBRN capacities of South-east Asian countries in addressing CBRN risk mitigation through specific activities related to:

- Capacity building on crisis management for CBRN first responders (**Component 1**);
- Capacity building in biorisk management, including biosafety, biosecurity and waste management (**Component 2**);
- Awareness raising concerning CBRN risk mitigation and technical support to strengthen legal framework (**Component 3**).

In this framework, Component 2 specifically aims at **enhancing biosafety and biorisk management capabilities** via a series of activities organized into three Work Packages (WPs):

- Coordination, analysis and training course development on biosafety, biosecurity and biorisk management (WP3);
- Assessment of existing capabilities relevant to biosafety and biorisk management (WP4);
- Risk assessment, transport and management of hazardous biological waste (WP5).

Under WP3, two main educational pathways have been developed, one devoted to biorisk management – the Biorisk Expert Team (BET) Training Program – the other one to facility design and construction – the **Design Expert Team (DET) Training Program**.

The present booklet originates from the training material and training guides provided to the DET members during their training on design, construction, operation and maintenance of biological facilities. It is aimed primarily at architects, engineers and other construction industry professionals living and working in Southeast Asia but has much wider, universal application. It is intended to provide a broad introduction to construction industry professionals and designers who may have no previous knowledge of designing or constructing biological facilities, but it could be valuable and informative also for project managers/directors and other members of a lab owner/operator team. It is hoped that by being aware of the ideas in this booklet, and if those professionals then later

become involved in a project to design, to construct or to refurbish a biological facility; then they will be armed with a basic level of knowledge that can help them to better understand the needs of the users and can also then be expanded upon by reference to more complete design guidance.

Our main reference for this booklet is the **WHO Laboratory Biosafety Manual**[1] (third edition, 2004). This manual establishes the bases of biosafety, with a special concern for developing and low resource countries. It also sets a number of good practices and recommendations that can be seen as standard for low resources countries. Most of these principles and good practices stay valid despite the progresses of life sciences since 2004. However, at the moment this project 46 booklet is being produced, an up-date of the WHO Laboratory Biosafety Manual is in preparation. This new version is announced as likely to bring some major changes. Among these, there will be a less strict link between the biosafety levels and the application of standard containment measures. Such measures will then need to be defined and justified on the basis of risk assessment. Also, engineering controls will less be considered as the solution by themselves, but rather as a way to facilitate good and safe work practices. This new approach will certainly give rise to much more logical and practical facility design, resulting in more adapted and sustainable facilities: so of a special interest in countries with significant resource limitations combined with a high burden of infectious disease. By understanding the nature and purpose of **biological facilities, biosafety, biosecurity and biological risk assessment**, and, by having a basic understanding of common **design features and equipment**, designers should be better prepared to adapt to the new way of approaching the design and construction of biological containment facilities.

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[1] http://www.who.int/csr/resources/publications/biosafety/en/Biosafety7.pdf

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The authors and the Project Team of ASST Fatebenefratelli Sacco are grateful also to all the colleagues and the organizations of the countries participating to Component 2 - Work Package 3 of Project 46 for their continuous support and positive contribution to the implementation of the DET Training Program, including the National Focal Points of each country (Brunei Darussalam, Cambodia, Lao PDR, Malaysia, Myanmar, the Philippines, Thailand and Viet Nam), the National Teams, and the institutions that hosted the DET training sessions in Manila (Research Institute for Tropical Medicine - RITM) and Hanoi (National Institute of Hygiene and Epidemiology - NIHE), as well as Brunei Darussalam for hosting the DET Final Workshop and allowing the visit of the National Isolation Centre - NIC. We are especially indebted to the DET members: Juliana binti Haji Zaini, Ruzanna Musfirah binti Hj Saji, Dk Hjh Adawiyah Pg Hj Jaberudin, Sopheap Sam, Ken Kettyarath, Tith Chann Bophal, Kanika Rin, Maleeny Phinith, Manorot Phinith, Nimmane Phanpaseuth, Chanthaboun Sopha, Souksaikham Singvongsa, Xaybandith Xayavong, Amrish Shah bin Osman, Chubashini Suntharalingam, Ahmad Razi bin Mohamed Yunus, Vijay Kumar, Saiful Azrin bin Fudzil, Kay Thi Oo, Cho Thanda Tun, Khine Win, Jose Nolan M. Vicente, Mary Ann A. Espina, Nathaniel B. Diola, Lauro C. Canceran, Allan A. Domingo, Phanida Kesornprasert, Kultira Tepsubhornkul, Kriengsak Srikaewkthaew, Truong Quan Thuy, Dao Hoang Anh, Le Thi Hoi, Huynh Thi Kim Loan, Tran Van Quy. They have been proactive participants and true protagonists of the DET Training Programme. We would also like to thank Irma R. Makalinao, Fedelino F. Malbas Jr., Nguyen Thanh Thuy, Viji Vijayan, the reviewers of this Booklet for being generous with advice on how to improve it and refine it. A special thank you to George Saralis-Wheatley, the young graphic designer who provided the team with most of the sketches included in this work. We are also appreciative of our Consortium Partners, the International and Ibero-American Foundation for Administration and Public Policies (FIIAPP) and FORMIT Foundation, with whom we have the pleasure to work towards the achievement of Project 46 overall objectives.

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1. Life sciences, biological risks, biosafety and biorisk management

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1.1. Introduction

Life sciences cover a large range of activities that deal with living organisms. Many of these activities are conducted in diagnostic or research laboratories or other specialised facilities such as, animal housing facilities, quarantine units, greenhouses, or biological production facilities. And many of these activities involve the use of organisms and other biological materials that may present a hazard for the people who handle them, but also for the outside community or the environment, i.e. mainly animals or plants, in case of escape and dissemination. Biosafety, and more broadly **biorisk management**, aims at preventing, limiting or, more generally, controlling these risks. The **biorisk management approach** is based on a number of measures that involve **work practices**, **personal protection**, **containment infrastructure**, and **management practices**. The purposes of this first chapter are to explain the main notions and principles that architects and engineers likely to work in this particular field should know and understand, and to present the main references and points of view adopted in this booklet.

1.2. Some definitions

Biosafety
Set of measures aiming at protecting the personnel, the community and the environment from the risks of non-intentional exposure to hazardous biological agents.

Biosecurity
Set of measures aiming at preventing the voluntary misuse, theft, loss or intentional dissemination of biological agents or biological toxins (e.g., as biological weapons, for terrorist purposes, sabotage of containment facilities…).

Biorisk management
Global approach aiming at preventing or limiting all the risks arising from biological agents and materials; biorisk management encompasses both biosafety and biosecurity.

Biological agents
Living microorganisms ("microbes", i.e. bacteria, viruses, microscopic fungi and parasites) and, by extension, cells and cell lines used in culture.

Biological materials
Biological agents and all materials that are likely to contain biological agents (e.g., blood and serum samples, biopsies and other samples taken on patients or infected animals, samples from sewage waters and other contaminated environments, untreated hospital waste…).

Pathogens
Biological agents that are likely to cause infection and disease.

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Biological containment, or containment
Set of measures aiming at preventing the exposure or dissemination of biological agents or materials; containment is generally seen as a combination of physical measures, work practices and their management.

1.3. Principles of biosafety, containment and biorisk management

Biosafety is mainly a matter of putting barriers between the hazardous agents and materials and the personnel, the community and the environment. These barriers can be of different nature: laboratory devices or equipment, Personal Protective Equipment (PPE), the facilities themselves with their containment features… However, since laboratory work consists in handling, cultivating, analysing, modifying, using these biological agents and materials, physical protective barriers are always tightly associated with work practices. And, given the complexity of the laboratory activities and the importance of human factors, management aspects appear as a third major component of sound biosafety and biosecurity. For these reasons, work practices, infrastructure and management practices should always be considered as a whole in biosafety and biorisk management, even when planning for and designing new facilities.

From a technical point of view, we usually make a distinction between two levels of barriers: primary and secondary containment.

Primary containment consists of all the measures that aim at (1) protecting the laboratory personnel, and (2) avoiding a contamination of the laboratory, which could result in indirect exposure or possible dissemination. Primary containment devices and measures are for example the tubes or flasks in which biological agents are kept, equipment like bioreactors or fermenters, protective equipment like biosafety cabinets (see 3.1), and associated work practices. Personal protective equipment (PPE) are usually considered as a complement to primary containment devices.

Secondary containment aims at protecting the outside community and the environment from the biological materials used in the facilities. Examples of secondary containment devices and practices are the laboratory structure itself, the fact that laboratory doors and windows are kept closed, anterooms or airlocks, decontamination autoclaves, hand washing when exiting the lab, the packaging of the infectious materials and waste to be transported outside the facilities, among others.

A number of other measures come in complement to these primary and secondary containment measures: limited and possibly controlled access to the facilities, emergency procedures, personnel information and training, inventory and record keeping, inspections and audits, medical surveillance, vaccination, etc.

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Regulations and guidelines classically define four 'Biological Safety Levels' (BSL) or 'biosafety levels' (BSL1 to BSL4)[2], in response to increasing levels of risks and therefore reflecting increasing containment requirements: that is, increasing requirements regarding physical containment and associated work and management practices:

- **BSL1**, for biological activities representing no or negligible risks, such as some teaching laboratories or some molecular biology activities in which only non-pathogenic agents are used;
- **BSL2**, for activities that present some biological risks for the laboratory workers, but a relatively limited level of risk for the community and the environment, such as many diagnostic and rather basic activities that do not involve the culture of some of the most hazardous agents;
- **BSL3**, for activities involving the use of pathogens that may present a higher hazard for the exposed personnel and also would pose a significant risk for the community or the environment in case of dissemination, such as some diagnostic and research activities in which hazardous agents are cultivated;
- **BSL4**, for the activities involving the most hazardous pathogens for the exposed individuals, the community or the environment; BSL4 facilities will not be considered in this booklet.

BSL1 facilities are basic facilities, in which general safety practices are applied, generally together with quality management practices (good microbiological techniques, good laboratory practices, good manufacturing practices), but no specific biosafety practices.

Biosafety practices apply as of BSL2. The general principle at BSL2 is that safe work and management practices, together with some primary containment and rather basic personal protective equipment are sufficient to control biological risks.

The main difference between BSL3 and BSL2 facilities is the importance of secondary containment at BSL3, which is logical since the purpose is also to protect the outside community and the environment. Physical containment measures go along with stricter work practices and, generally, stricter management practices, including from a biosecurity standpoint.

1.4. Biological risk assessment

One cannot control the risks of a given activity without a good knowledge of the activity and a good appreciation of the risks it may generate, especially in a complex work environment. Thus, the assessment of biological risks, or **biorisk assessment**, appears as the cornerstone of biosafety and biorisk management.

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[2] BSL is one of the most used terms at international level, but many others can be found in various regulations and guidelines. They are most generally based on the same principles and are equivalent.

Risk assessment aims at defining the preventive and protective measures that need to be implemented in order to control the risks posed by an activity to an acceptable level. Risk assessment thus requires some evaluation of the likelihood of exposure to harmful events and the consequences of such an exposure.

Biological risk assessment is classically a **two-step approach**:

- Step 1: **Identification and characterisation of the nature and level of hazard** of a given biological agent – **hazard** being defined as the potential to cause harm (e.g. a hazardous substance, agent, animal, etc.);
- Step 2: **Analysis of the activity** in order to define situations that could lead to an exposure or dissemination, either during normal operations or in case of incident, and determine the level of risk – "risk" relating to the likelihood and consequences of exposure to the hazardous agent in a given context.

Characterisation of the nature and level of hazard of a biological agent (Step 1) requires considering numerous characteristics, such as its biological features, its modes of transmission, its transmissibility and pathogenicity, its resistance to environmental factors, to heat, to disinfectants and drugs, the severity of the disease caused, etc. To facilitate the definition of the level of hazard, biological agents have been classified in **hazard groups** (HG1 to HG4) 1 to 4[3], translating increasing levels of potential harm. These hazard groups are artificial and a simplification, though. Moreover, most of the official or published classifications of biological agents in hazard groups have been established in Western countries, and therefore do not necessarily represent the situation in other countries. For example, a given agent may be considered hazardous in a developed country because most of the population there is vulnerable, while most populations from low-resource countries may be immune due to harmless exposure at young age.

Once the hazard is characterised and a hazard group ascribed, one then analyses the risks of the different steps of the activity carried out with that biological agent. The result of this analysis is the risk class of the activity. Note that the different steps of a large activity may not necessarily be ascribed the same risk class, depending on factors like the concentration of the agent, the scale of the activity, the possibility to create aerosols, and so on.

It is finally the risk class of the activity that defines the biosafety level (BSL), the nature of the hazard and risk defining what specific measures need to be put in place in addition to the measures already applicable at that level. Thus, the biosafety level (BSL) that is required does not necessarily correspond to the hazard group of the biological agent, but rather to the level of risk of the activity. Moreover, some specific measures may be required or omitted due to the specificities of the agents and the activities.

[3] Erroneously referred to as "risk groups" in numerous official documents.

Risk assessment must be conducted by those who know the best the agents and activities to be assessed, that is the scientists, with the support of the biosafety officer and possibly other safety and health professionals. Risk assessment is generally, at least in a biorisk management approach, submitted to some systematic review and approval.

Risk assessment is normally conducted: before new project and activities are launched, or when activities undergo some changes, or following an incident, etc. Moreover, risk assessment of the future activities needs to be done, by the owner and users, before starting to design a new facility, in order to define users' requirements such as the required biosafety level(s), particular design features or engineering controls, etc.

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1.5. Main references and points of view adopted in this booklet

The main published reference used for this booklet is the **WHO Laboratory Biosafety Manual** (2004)[4]. Although somewhat dated, for instance compared to the progresses of biological sciences during this last decade, this manual is one of the only official and truly international guidance documents that take into consideration countries with limited resources. Moreover, most of the principles stated in the manual – although some have been misinterpreted – remain fully applicable today.

Other regulations and guidelines are available[5]. Most of these were developed in Western countries, originally to respond to national needs but then promoted at international level (without being truly international). They have thus been quite extensively used in developing countries. Although these regulations and guidelines may reveal useful in a number of cases to consider possible options to solve specific issues, the standpoint adopted in this booklet is to avoid considering them as suitable general references. This position is based on the observations made in Southeast Asian and other limited resource countries, where a number of facilities that were designed and built according to Western standards[6] have revealed unsuitable for their intended use, and unsustainable due to excessive operating costs and lack of local maintenance capabilities.

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4 http://www.who.int/csr/resources/publications/biosafety/en/Biosafety7.pdf

5 Main ones to be listed here:
"Biosafety in Microbiological and Biomedical Laboratories" ("BMBL"), 5th ed., CDC-NIH, USA (https://www.cdc.gov/biosafety/publications/bmbl5/BMBL.pdf)
"Canadian Biosafety Standards", 2nd ed. (2015), and associated Guidelines and Handbook, Public Health Agency of Canada (PHAC) (https://www.canada.ca/en/public-health/services/canadian-biosafety-standards-guidelines/second-edition.html)
"Safety in laboratories. Part 3. Microbiological safety and containment", Australian / New Zealand Safety Standards, AS/NZS 2243.3:2010
"Biological agents: managing the risks in laboratories and healthcare premises", ACDP, UK (http://www.hse.gov.uk/biosafety/biologagents.pdf)
The management, design and operation of microbiological containment laboratories (http://www.hse.gov.uk/pubns/priced/microbiologyiac.pdf)

6 This is actually equally true for facilities designed and built by companies from Asian countries with a high economical level.

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The same general observation applies to a number of sophisticated equipment items (e.g. some types of biosafety cabinets, some types of autoclaves, some incinerators etc.).

It may also be worthwhile to mention here the trends that are being developed in the coming up-dated **WHO Laboratory Biosafety Manual**[7]. Also based on observations made in developing and limited resource countries, the proposed way forward is to use a practical, **risk- and evidence-based approach**[8] rather than follow standards that often reveal excessive and without link with the actual nature of the risks. The new trend is to promote flexibility and to give much more importance **on Good Microbiological Practices and Procedures (GMPP)**, on human factors and on training ("the best designed and most engineered laboratory is only as good as its least trained worker"), rather than unnecessarily complex and unsustainably expensive facilities.

[7] "WHO laboratory biosafety manual – Revision update", lecture presented by Kaz Kojima (WHO) at the 12th Annual Asia-Pacific Biosafety Conference, Aug. 2017.

[8] As for instance the "Tuberculosis Laboratory Biosafety Manual", WHO, 2012 (http://apps.who.int/iris/bitstream/10665/77949/1/9789241504638_eng.pdf)

2. Common factors affecting the outcome of the design and construction of biological facilities

2.1. Experience

Previous experience of biological facility construction projects can be very positive for any new construction or refurbishment project. Experience of designing or constructing similar facilities such as hospitals or healthcare centres can also be valuable. In the same way a lack of experience, and more critically a lack of clear understanding can be harmful and have adverse effects on such projects.

It is therefore very important if possible that at least one key member of the design team has worked on such (or similar) facilities in the recent past. Of course this is not always possible, and everybody has to start somewhere.

In such cases it is strongly advised that appropriate direction and advice is sought. This can be achieved by gathering suitable guidance and making a positive effort to understand completely all critical aspects and features. It is also quite common to undertake visits to similar new facilities, to speak with the users of these facilities and attempt to learn valuable lessons from them.

Visiting similar facilities in the region and sharing the experiences and lessons learned can be a very positive way to improve chances of project success. It might also be possible to consider the knowledge and advice available from members of your own professional organisations and groups, in particular there may be groups with special interests in biological facilities, as well as national and regional biosafety associations. These can be a useful resource. The members of the EU CBRN Project 46 DET (& BET) would be such an interest group.

Good preparation then can be a substitute, if necessary, for good experience.

2.2. Teams and people

In order for a new biological facility to be designed and constructed there will need to be a number of teams involved, sometimes these teams will overlap and people may belong to more than one team. It is also normal that the structure and membership of teams sometimes changes during the project life cycle. The main types of teams commonly found are as follows:

- Client/owner/user team
- Design team
- Construction team/contractors team

2.2.1. Client/owner/user team

This team is normally made up of key individuals (or their representatives) inside the organisation planning to own or use the new facility. They will normally have an important part to play in the conception, use and/or operation of the proposed new facility. This team might include:

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- Facility director
- Departmental head
- Lead scientific officer
- Biological Safety Officer (BSO)
- Health and safety professional
- Quality manager (if not also the BSO)
- Financial/legal officers
- Head of maintenance/engineering (or their representative)
- Project manager (for the construction project on the clients team)

2.2.2. Design team

This team is normally made up of designers, such as architects and engineers. It might start off with just one or two key individuals who can help to develop the early concepts with the client/owner team and then grow in membership as the project grows. This team tends to become involved once the client team has established some basic ideas of what they need, so there is often already a broad outline plan and even a budget in place. Typical design team members include:

- Architect
- Project manager
- Laboratory/facility planner
- Quantity surveyor
- Structural engineer
- Services engineers (mechanical, electrical, plumbing)
- Landscape architect

2.2.3. Construction team

Construction team are often the last team to be formed, but not always. They will typically comprise different members depending on the phase of the project with some needed to measure and price for the work and others to execute it. There may be one or more key individuals who usually follow the whole project life cycle. This team will often include the following members:

- Project manager
- Construction manager
- Quantity surveyor
- Engineers and surveyors
- Main sub-contractor representatives

Each of the three separate teams described above will have different goals, aims and motivations. The closer these are unified the higher the probability of a successful outcome. It can be a complex task attempting to have each of these teams working towards the same goal for the duration of a project.

Although different companies and organisations may demonstrate good previous experience of designing or constructing biological facilities on paper, the ultimate success of any project relies normally on just a few individual people. Choosing the right people for each critical role can

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make huge differences to project success. Keeping these individuals motivated, interested and enthusiastic will normally always help to improve final project outcomes.

2.3. Communication

Communication is at the heart of all construction projects and **good communication** is critical to success. The most important communication pathway in the early phase of a project is that between the client/owner/user team and the design team. When concepts are being developed and plans formulated it is crucial that each group communicates effectively with the other. Without clear and effective guidance and direction from the client team, a design team may misunderstand some of the key client requirements and this can cause the design to be inappropriate and unsatisfactory. There is a well-known cartoon often called 'the architects swing' which illustrates how various people in the various teams can perceive the same project from their different perspectives. A typical example of this humorous cartoon is pictured below. The end result can be very far from the original intent and additional miscommunication can occur when the construction team joins the project.

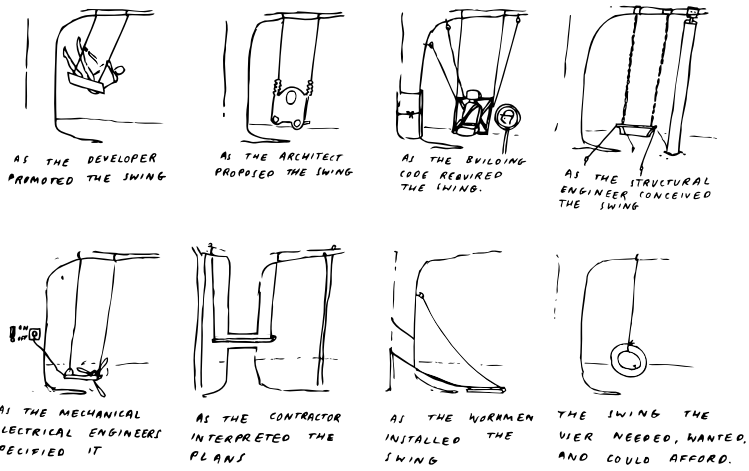

Figure 1. The architects swing

It will be necessary for each team to learn, at least in part, the language of the other teams - in order to improve communication. It is the job of the design team to make every effort to understand the needs of the user, then they must ensure the client team can understand and interpret their design proposals so that problems like the architects swing can be avoided. Of all the skills which the design team can share with the client team the most practical one is how to **read and interpret typical construction drawings**. A workshop on how to read, understand and question construction drawings held early in the process could really help to improve

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communication flow and so make great contribution to the improved understanding of the client team.

2.4. Clear user requirements

User requirements, often set out in a '**User's Requirement Specifications' or URS**, are a fundamental tool which must be developed and used to convey key information necessary to enable the design team to fully and completely understand the needs of the users (represented by the client/owner/users team). The greater the completeness, accuracy and detail contained in these user requirement specifications, the greater the likelihood of a successful project outcome. Previous experience here can be extremely valuable as can seeking advice and knowledge from similar organisations who have already completed successful similar biological facility projects in the same country/region.

Traditionally this process was known as 'establishing the brief', terminology still widely used. The clients brief sets out clear measurable targets for the design to deliver. It should be established as early as possible in projects and as completely as possible. It can also be used to help build the project budget - all the more reason then for it to be as complete and as accurate as possible – since project budgets once fixed and approved are notoriously difficult to change.

Often the URS or client brief begins to be established during a pre-project phase, possibly well before the design team becomes involved, it should be drafted by the users initially but may need to be supported by input from a suitable person who could be employed part time or on a short term basis to assist. One specific member of the user team should be tasked with its ownership and development. It should be **validated or confirmed at each project stage** in order to ensure the final design remains appropriate to the users' needs.

2.5. Project and programme management

An important part of design and construction **project management** is the **programme** (or schedule in the US terminology). If a project is late it can often impact on plans of the client/owner organisation to move into new buildings, to employ new staff, to commence a new research project or to deliver a key service. Many factors can cause delays but it is equally possible that the original programme was simply wrong, too ambitious or simply not well conceived. It is vital to ensure the project programme is fully accurate.

Here is another area then where experienced individuals can contribute to successful project outcomes. Project managers are usually responsible for drawing up project programmes and there is often more than just one programme developed during each project life cycle, often by the different project managers involved in each project. There may be a strategic master programme, held by the client/user group covering not

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only the project implementation but parallel activity like closing down an old facility or a staff relocation plan. There will be a project plan developed by the design team to manage their input and responsibilities and later there will be a construction programme possibly developed as part of the tendering process and used as a key indicator of the contractor teams' performance. This last type of programme is often contractually binding and sets out the target date for the completion of construction projects and handover. Here again not only the experience of the designers but an experienced contractor or construction project manager can generate and agree realistic programmes accounting for all of the likely complexities associated with biological facility construction.

Unrealistic programmes can lead to the compression of critical activities at the end of the project, such as commissioning, with a possible major negative impact on the final operability of the facility.

Experienced project managers can be very effective in ensuring realistic programmes are produced and then completed on time. They require good communication skills and a broad understanding of all aspects of their industry as well as a clear understanding of the client and user requirements.

One consideration when developing any programme is the inclusion of some flexibility to cover unpredictable events, this is often addressed by including 'float'. Float is a contingency built into a programme which can absorb a limited amount of slippage. Size of any float must be proportionate to the overall project timeframe.

2.6. Costs and cost control

Along with programme, **cost** is another major element of a design and construction project. We often hear of projects which are late and over budget – it is rare for anybody to concede that the project programme was wrong or the original budget insufficient. So it is important to get these right, and as early as possible.

In the early stages of most projects a timeframe and a cost plan will be established. This may be part of a 'pre-project planning phase' - before any construction professionals are involved. Good cost data on the construction of new biological facilities is not always available since they are constructed infrequently and most are unique. Costs can easily be underestimated and once fixed may be difficult to change as the scope of the project develops. When establishing a **project budget** it is important then to understand and include for all of the costs associated with both the design and construction as well as operation of a new biological facility. Project budgets must consider not only all initial capital costs but need also to look forward and consider the realistic owning and operating costs of each facility. Failure to fully assess the 'whole life' owning and operating costs of facilities can later have tragic consequences, especially on biosafety and biosecurity if the facility cannot be properly operated and maintained due to a lack of operational funding.

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In order to establish realistic project budgets, and so define an Approved Project Cost (APC), the following cost aspects need to be taken into account (there may also be additional project specific costs, as all biological facilities are unique):

- **Construction costs**, including for
  - Commissioning and hand-over
  - Special testing of materials and assemblies
  - Possible mock ups
  - Quality control and quality assurance costs
  - Safety-related costs
- **Programme management costs**, including
  - Training costs
  - Start-up costs
  - Relocation and moving costs
  - Operations and maintenance costs (annual and forecast future for at least a minimum specified operating period, say 5 years)
- **Major equipment and fit out costs**, including for
  - Facility equipment, moveable and benchtop equipment
  - Furniture, Fixtures and non-laboratory Equipment (FF&E) (desks, workstations, chairs, conference room furniture, furniture for common or break areas, etc.)
  - IT, telecom, computer cabling and the telephone system
  - Computers and audio-visual equipment
  - Signage and artwork
  - Fire prevention and suppression measures
- **Indirect 'soft' costs**, including
  - Architect/engineer design service fees and consultant fees
  - Construction change orders
  - Legal fees
  - Permits and filing fees
- **Contingencies** (e.g., 5% of total budget), for unexpected costs such as poor ground conditions or hard rock making digging of basements or constructing foundations more expensive.

Once a realistic approved project cost is agreed and there is a well-considered and complete programme in place the likelihood of achieving both may increase considerably. In both it is always helpful to consider contingency, a contingency sum can be incorporated in a project budget as a fixed percentage of the total cost to cover any additional costs which might arise. Similarly providing some float in a project programme as described above can be used to adapt to circumstances which might otherwise lead to the project being completed late.

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2.7. Project documentation

Having established already that communication is a critical component of project success, project (design) documentation is the principle method for the three teams to communicate, understand and agree what

is required and how it is to be achieved. The design process normally follows logical well established stages from conception to completion. During each project stage the design team (or construction team) should report to the client team what is being proposed or completed. These design (or construction) stage reports are fundamental in ensuring that the client and user groups fully understand the detailed design or construction as it develops. It is incumbent on design and construction teams to provide this information in a format and with the necessary support to ensure absolute clarity to the owner/client/user team. This **design or construction documentation** may need to differ from that provided to the builder or installers. It may need to be developed specifically to ensure clear and absolute understanding in order to enable complete and comprehensive agreement that the design and construction proposed at each stage continues to meet the users' requirements.

2.8. Project supervision

Every stage leading up to the construction of a biological facility is important to its overall success, but there can sometimes be a clear change of emphasis once the design stage is complete. The level of input provided by the design team will naturally reduce after the detailed design is completed, but it is crucial that a correct level of involvement is sustained to ensure successful completion. This should be agreed between the client and design teams as part of the roles and responsibilities in order to ensure an appropriate and sustained level of quality control. It is needed to ensure that the intent expressed in the design documentation is actually achieved and that the completed project meets fully all of the users requirements originally defined at the beginning of the project. The level of design team involvement needed will typically be proportionate to the complexity of the facility.

2.9. Quality control

Biological facilities, even simple ones require a high degree of quality control. This is needed throughout all of the project stages, including and especially during the whole construction process. For instance, it should not just be limited to verification of the application of finishes, since the integrity of the final finishes is highly reliant on the stability and completeness of the underlying structure and fabric. The design team should ensure the correct clarity and detail in the design documentation to ensure that the appropriate care and time is taken to achieve the correct results and therefore make every effort to reduce the likelihood of later problems.

One practice that can help with this process is by producing 'mock-ups' or 'test pieces' that can be used to first agree and then measure the final work. It can also be extremely helpful if the client team employs an independent representative to **monitor quality control**. Traditionally in the UK this person is called the 'clerk of works' and is usually based on the

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construction site full time from the beginning to the end of the construction phase of the project.

Of critical importance for quality control is the commissioning phase which will typically be conducted normally during the latter stages of a project. Here it is vitally important to plan the correct amount of time from the project outset and then to ensure that the planned duration is safeguarded and all work is done correctly.

2.10. Commissioning and handover process

Handover is normally the point in a project where the ownership and responsibility for the completed building passes from the constructor **to the client/owner**. This step corresponds to the end of the **commissioning phase conducted to verify and demonstrate that the facility is built according to the specifications** and ensuring it will operate according to the specified or normally expected performances.

Due to the criticality of many aspects of biological and containment facilities it is very important that a clear definition for **completion** is set out. In the construction of a biological facility it is very important to establish very early on that before it can be handed over it **must be fully complete and ideally be defect free.**

The commissioning phase must therefore conclude in a clear agreement between all the different teams involved in the project that all of the construction and installation work is fully complete, in accordance with the specification and that all specified testing has been done and all specified criteria have been met. For this reason, it may be interesting to develop a commissioning and validation master plan during the design phase. On complex projects an independent commissioning agent can be hired to check all of these things in order to reassure the client/user team that the project is complete and in a suitable condition to be handed over.

Sufficient time needs to be allocated to commissioning and then safeguarded; correct commissioning and verification is vitally important to ensure that the facility meets the specifications and can be operated safely. Just to give an idea, the commissioning of some sophisticated containment facilities can take up to 6 months.

The handover also includes the provision of all the needed technical documentation to the users, and more especially those who will be in charge of managing and maintaining the facility.

2.11. Operating and maintenance information

For the correct and safe operation and maintenance of a biological facility it is vitally important that the **information** provided at the project handover is **accurate, concise and sufficient**. Too often the operating and

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maintenance manuals are poorly constructed, incomplete or even missing completely at project handover. Enshrining the importance of these critical documents in both the contract and in the design documentation can help ensure they are fully complete, delivered in time and most important of all, fit for purpose.

Operating and maintenance manuals should contain not only clear, concise instructions on how to operate and maintain the facilities but also contain all of the completed commissioning data demonstrating full function at time of commissioning. Additionally they should contain 'as built' drawings for all elements and services in accordance with the final and complete installation.

It will be necessary for the design team, and possibly the independent commissioning agent, to fully review, to comment on and finally to approve the operating and maintenance manuals prior to the project handover. If the client team includes a representative of the maintenance team or department they too should also be part of this review in order to ensure the operating and maintenance manuals are sufficient for them to take over the operation and maintenance of the facility. This should also include where necessary specific training on specialized systems as well as any needed access codes and software back-ups for the controls systems where these are included in the facilities building systems.

2.12. Training

Training should be an integral part of the delivery of a project and may include different categories of training for different groups. The training should be programmed or scheduled to be in place at the correct time and may be conducted 'off site' or 'on site' or sometimes both. Finally training on the actual constructed building may need to take place before or after handover.

Training can include the operation and maintenance of the facility and its engineering systems but often will include specific training on key equipment such as autoclaves, BSC's and other equipment provided. In some cases the training may include external agencies such as the fire brigade in order to obtain the necessary operating permits.

3. Common equipment of biological facilities that can affect the design

3.1. Biological safety cabinets (BSCs)

For some working practices used in biological facilities a risk exists of exposing the worker to biological agents in an aerosolised form. Based on biological risk assessment, one or more biological safety cabinets (BSCs) may need to be included in the design of a new facility.

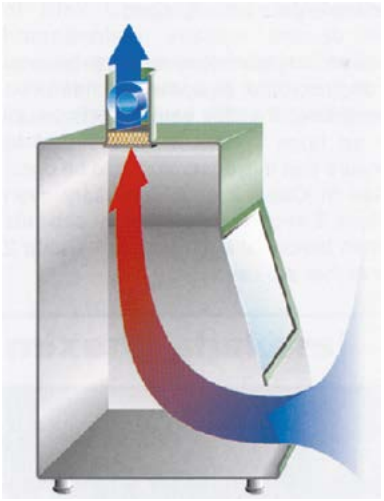

Figure 2. Class I Biosafety Cabinet

BSCs are **designed to protect the worker, the laboratory and the outside environment from contamination and exposure to hazardous aerosols**. Some BSCs are also designed to protect the actual work being done inside the BSC. There are three main types of BSCs: Class I, Class II and Class III.

A **Class I BSC** draws air in through an opening at the front and passes it out through a **HEPA filter (High Efficiency Particle Air filter)** before it is discharged either inside or outside of the laboratory.

A **Class II BSC** is more complex: part (usually ca 70%) of the air drawn through the front grille is recirculated through a HEPA filter before being delivered as a laminar flow on the working area, while the rest (i.e. ca 30%) is discharged through another HEPA filter, either to the room or possibly to the outside.

Figure 3. Class II Biosafety Cabinet

A **Class III BSC** is a kind of closed system, or isolator, with HEPA filtered supply and exhaust air, maintained at a negative pressure. Handling in a class III BSC is carried out through long gloves which are a part of the cabinet (but can be changed).

Class II BSCs are the biosafety cabinets that are the most frequently found in biological laboratories, both in Western countries and in SEA. The main reason for this is that they have been designed also for product protection. Product protection is ensured by the fact that HEPA-filtered air is blown in a laminar way on the work surface.

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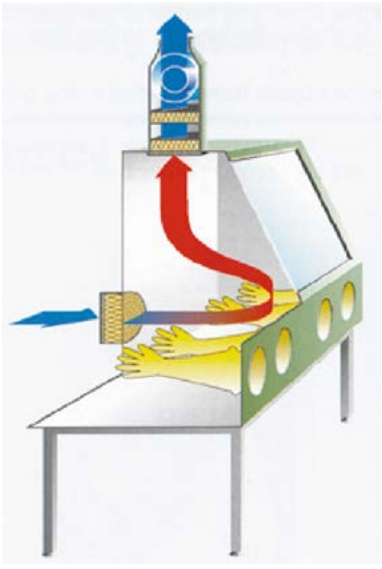

Figure 4. Class III Biosafety Cabinet

However, it may be useful to point out that class II BSCs were initially non-protective laminar flow benches that have been modified to offer some personal protection. This explains their relative complexity, which makes them less robust, more sensitive to disturbances, more difficult to use and more expensive to maintain. More importantly, they are less protective than class I BSCs, due to the sensitivity of the airflow barrier at the level of the front grille. In addition, due to their complexity and the cost of validation and maintenance, many are not operated or used in appropriate conditions, which may result in major default of personal and product protection. This is particularly true in SEA, where in a survey of biosafety level (BSL) 2 and 3 laboratories in 7 countries in the Asia-Pacific region 30 % of the class II BSCs tested were poorly designed, incorrectly installed, not certified, or being operated improperly[9].

In comparison, class I BSCs, although more protective, less expensive and easier to use and maintain, are barely present in most facilities, even in low resource countries. The fact that they were not designed to offer product protection is probably one reason, together with a strong marketing culture in favour of more sophisticated and expensive class II BSCs.

However, class I BSCs, although not *designed* for product protection, are likely to offer good product protection using the standard microbiological practices that would be used on a bench (including using a moderate flame, which is definitely not advisable in a class II BSC because of the possible build-up of alcohol vapours).

Class III BSC are only present in very few facilities. Their use is mainly reserved to at risk activities on highly hazardous pathogens.

3.1.1. How Class I & II BSCs affect biological facility design

Class II BSCs draw air in through an open front grille, which constitutes the protective barrier. This protective barrier is very sensitive, since it is the place where the positive pressure laminar air from the working space and the negative pressure air sucked into the cabinet neutralise each other. It is therefore extremely important, for both personal and product

[9] "A Biological Safety Cabinet Certification Program: Experiences in Southeast Asia", Whistler T., Kaewpan A and Blacksell S., Appl. Biosaf. 21: 121-127 (2016) (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5053331/)

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protection, that this barrier is not disturbed by air movements in the room.

Class I BSCs are less sensitive to location, but this must still be considered in the design and layout of new or modified laboratories. Class I BSCs when directly ducted to the outside can also provide a negative pressure in the room and so induce the necessary inward airflow for some containment and elimination (through filtration) of aerosols.

BSCs, and in particular class II BSCs, must therefore be located away from open windows or doors, air flows from ventilation fans and air coolers, or air currents caused by moving people, machinery or hot appliances. In particular, the impact of complex ventilation systems (HVAC) on class II BSCs should be evaluated, and more especially the position of the supply and exhaust grilles studied in function of the location of the BSCs. From this point of view, an air supply diffuser is likely to provoke significant disturbance of the cabinet airflow, which is not the case of an exhaust grille.

Also, all BSCs, even small ones, are quite large and so they need to be planned into the architectural design early.

Deciding where to put BSCs in a facility should be considered very carefully to try to minimise or eliminate all possible unwanted air movement.

The figure below pictures different siting options.[10]

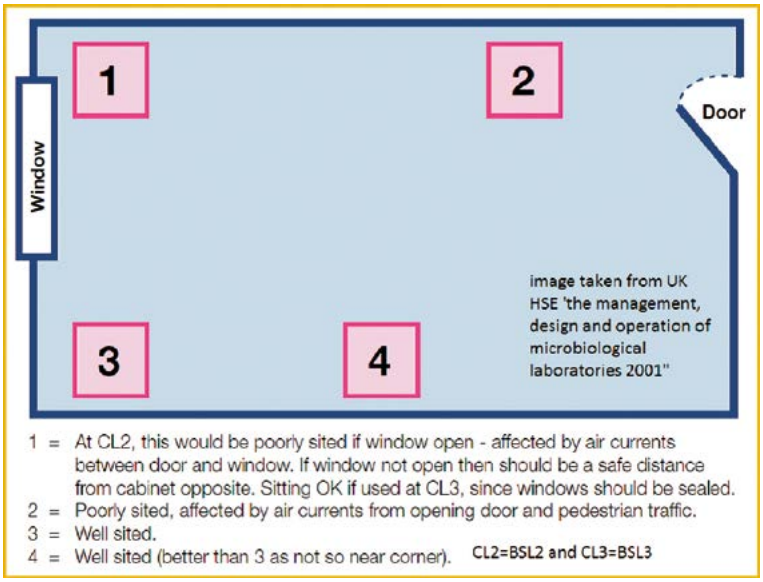

Figure 5. Guidance on the location of BSCs

[10] Excerpt from 'The management, design and operation of microbiological containment laboratories' ACDP HSE UK (http://www.hse.gov.uk/pubns/priced/microbiologyiac.pdf)

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3.2. Autoclaves

Autoclaves are devices that allow **treating materials with water vapour at a temperature higher than 100°C** made possible at higher pressures. They are mainly used to sterilize materials, equipment and media – sterilizing meaning destroying all forms of life including resistant spores. They are also used to treat biological waste, more precisely to decontaminate them – decontaminating meaning treating materials to make them safe for further handling or use.

All autoclaves use steam under pressure rather than dry heat to perform their function. They comprise a pressurised chamber that is loaded and closed, heat is then applied or steam injected and once the correct temperature and pressure is achieved a time must elapse before the cycle is complete. **The usual sterilisation and decontamination parameters are 121°C during 15 minutes**. The chamber must then be allowed to cool before it is opened (for safety reasons, especially where any liquid under pressure could rapidly vaporise).

Autoclaves come in many sizes, shapes and types. They range in complexity from something resembling a domestic pressure cooker up to very large machines needing their own special rooms; sometimes double ended machines are used through which loads can be passed from the dirty side of a biological facility barrier to the clean side (or vice versa).

Figure 6. Gas heated pressure cooker type autoclave

From a designer's viewpoint it is **important to understand the quantity, size and type of autoclaves which may be needed in a biological facility**. Especially for large and fixed autoclaves (other than the simple bench top ones), space needs to be provided for their location and utilities are needed for their safe and reliable operation.

Moreover, large and specific waste decontamination autoclaves may require a separate, ventilated room, and their location, especially of double-door *pass-through* autoclaves, can have a major impact on the material flows and the layout of a facilities floorplan. When space is allocated to positioning autoclaves it should also be considered where the material to be autoclaved will be placed before the machine is loaded and where it will be placed after the cycle is completed.

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Figure 7. Bench top electric autoclave

So for a machine which occupies 1m^3 (so 1000mm wide, 1000mm deep and 1000mm tall for instance) it may be prudent to at least allow the same space for material storage prior to loading and the same again after treatment, making a total space requirement of 3000mm wide, 1000mm deep and 1000mm tall. It is also very important to ensure good access for autoclave maintenance.

Figures 6, 7, 8, and 9 are examples of typical autoclaves found in regional biological facilities increasing in both size and complexity.

Figure 8. Floor mounted electric autoclave (wheels allow movement)

Figure 9. Large fixed floor mounted autoclave with automated loading door

3.3. Other equipment likely to affect design

Laboratory equipment can require space, and most of them require electricity or other utilities that can be very specific. Moreover, they tend to produce heat, which will need to be taken into consideration when designing the cooling and/or ventilation systems. It is thus important during the early project stages of any new or refurbished biological facility for the design team to obtain a **detailed inventory of all equipment** to be included or provisioned in the design. Some of this equipment may be owned already and will be relocated into the new building, here it is possible to get details on sizes and utility requirements. For planned new

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equipment the manufacturers or suppliers can provide information on space needs and utility connections as well as scale drawings to be included in the design. However, some equipment may not have been sourced yet, but space will need to be provisioned as well as services, here it is important for the client and design team to work carefully in allocating suitable space to accommodate functions and equipment which may only arrive in the building many months or even years after the completed facility.

Biological facilities cover a huge range from small hospital diagnostic laboratories, through university or institute research laboratories, to very large vaccine production factories. It is impossible to consider all equipment here but many pieces of equipment are common and will need space allocated as well as utility provision (possibly including drainage), a short list of common equipment in typical biomedical laboratories includes:

- Fridges and freezers
- Incubators
- Centrifuges
- Analytical machines

Some biological facilities may also accommodate animals used in the study of biological agents. Such facilities can become quite complex and need also to consider the welfare of the animals being used. Ventilation and environmental conditions can be much more stringent than for facilities used only by human occupants. It will also be important to include adequate storage space and capacity for food and bedding.

Space should also be provisioned in biological facilities for **appropriate storage of equipment, materials and consumables** used in the daily work. It is generally better if storage space inside the laboratory is limited to what will be normally required during a working day or week or perhaps a month at most, with surplus stock being stored in a larger organised storage space outside of the main laboratory. This allows a clutter free laboratory working space and minimises wastage of clean materials in the event of some gross contamination.

Space should also be considered for the storage and movement of waste – this is one area that can be easily neglected and can affect good management of a biological facility for its whole working life. Ensure **waste quantities and locations are considered and included in the design** with areas clearly marked out on the plans for such uses.

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4. Common design features applicable to most biological facilities

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4.1. Handwashing

Provision for the **washing of hands before leaving a biological facility** should always be included – and should ideally be distinct from the sinks used for the other laboratory activities –. A dedicated hand wash basin, ideally with running water, should be located at the exit of each facility room where possible. A single tap with cold or warm water is sufficient. There should be sufficient soap to aid hand washing and some method for hand drying also available. Taps that can be operated without using hands are preferred and become required as the level of biological risk increases. Simple mechanical systems such as long lever taps, knee or foot operated controls may prove far more reliable than electronic sensor operated systems – especially in lower resource settings.

The **location, size and accessibility** of hand washing basins is very important, it may even be necessary to provide more than one in a busy facility. Ensure they are provisioned in the design with adequate space to be used correctly.

Pictured below are two actual existing examples of hand wash basins sketched from photographs, the one on the left is small and located in a tight corner making it difficult to use, the one on the right is a better size and shape so easier to use correctly and effectively. The left hand one is in a large central hospital diagnostic lab.

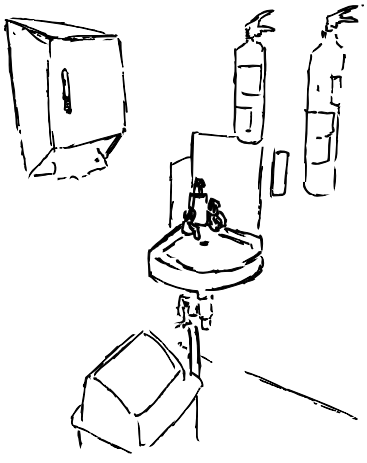

Figure 10. Hand wash basin – poor example (too small and too cramped)

Figure 11. Hand wash basin – good example (larger and more accessible)

4.2. Space

All guidance on designing biological facilities promotes the principle that the provision of **ample adequate space is fundamental to facilitate safe working** in a biological facility. To plan the right amount of space it is very important to establish predicted occupancy levels as early as

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possible in the design process and from that begin to determine the correct space requirements. Occupancy levels however are only part of the calculation, equipment, including sufficient space needed to safely operate, clean around (below and behind) and especially space needed to maintain that equipment is also fundamental to creating a safe useable facility space. As already mentioned, space should also always be clearly allocated to the storage and management of waste materials. Understanding likely people and material flows is an essential tool used to enable the designer to better understand the need for sufficient space for working, for movement and for storage.

Space will be needed for circulation, for the movement of people, samples and equipment around the room and this should carefully consider safe working space so that it is not disturbed – this is especially important in front of class II BSCs where movement of people can adversely affect personal and product protection. Space to load and unload equipment or samples from machines and space to open equipment doors (fridges, freezers, autoclaves) should also be managed. It can be very useful to indicate the space needed around, above or below equipment that should be left empty on facility design drawings with a dotted line and a note, for instance 'clear zone for safe operation of BSC – not part of circulation area'. It is also a good idea to extend this where practical on finished floors, a safe area can be indicated behind BSCs where pedestrian movement should be avoided – this is well illustrated in Figure 12 below sketched again from a photograph of a real lab.

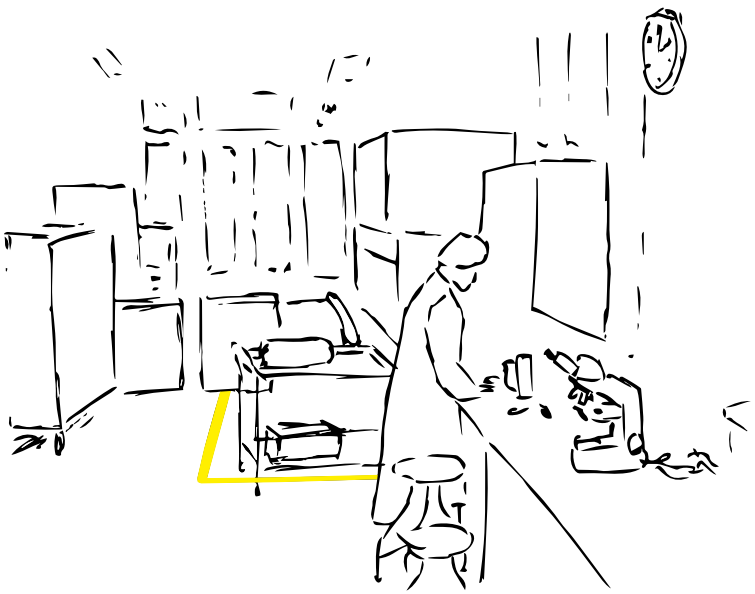

Figure 12. Example of safe zone around the BSC (indicated by yellow line)

The yellow floor tape indicates the safe zone around the BSC. Such reserved space should be respected and safeguarded. It is important also to understand that over the course of time additional equipment and people may be added to the facility that could result in compromise of

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the originally planned and needed 'ample working space'. Try to avoid overcrowding.

Space should be provided for the storage of materials needed for immediate use inside the facility, but only enough material for daily/weekly purposes in order to avoid clutter, to ease cleaning and decontamination activity and to reduce fire risk. Additional storage should be provided outside of the facility for the bulk storage of consumables. Space and storage immediately outside the laboratory should also be provided for outer garments and personal items as well as providing separated areas for eating and drinking – eating and drinking (and similar activities, such as smoking if permitted or the application of make-up) should always be prohibited inside the laboratory in accordance with all good guidance.

It can be useful to include changing rooms for removal of outdoor clothes and storage of personal belongings. It is also essential to ensure there is space for each laboratory either just outside or just inside or even a small lobby or anteroom for the storage and hanging of lab coats for the lab personnel. This needed space can often be ignored in error - but from biosafety point of view, we should promote not to bring lab coats out from the labs to public space e.g. office, canteen etc.

Some dedicated safe working and storage space is also likely to be needed for the safe handling of dangerous materials such as solvents, radioactive materials or liquefied gasses. This will need to be determined in close coordination with users in the formulation of their detailed user requirement specifications. Ventilated cupboards and fume hoods may also be needed.

As the complexity of biological facilities increases space will be needed for the engineering services which serve the facility. This can include technical plantrooms for ventilation equipment and controls as well as sometimes for drainage and for effluent collection, handling and treatment. In the design of technical support areas the same principles need to be applied to ensure adequate safe working space is provided in order to facilitate safe and reliable operation and maintenance of the building engineering services and equipment.

4.3. Surfaces

It is vital that surfaces provided as part of a biosafety facility perform in a way that reduces risks from contamination by biological agents. It is for this reason that surfaces including floors, walls and ceilings need to be **smooth, easy to clean, impermeable to liquids and also resistant to all of the chemicals and disinfectants normally used** in the facility, during both its daily operation and in the subsequent cleaning and decontamination processes.

Bench tops and working surfaces in particular need to be waterproof and be able also to resist the action of acids, alkalis, organic solvents and moderate heat.

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Surfaces need to be durable and hard wearing in order to reduce the level of maintenance needed to keep them in the correct good condition. It is very important that specifications are carefully written and quality control is rigorously exercised to ensure surfaces are manufactured and installed to meet stringent requirements. In particular, the application of paints, coatings and final finishes must be completed fully in accordance with manufacturer's instructions. As already mentioned, not only the final surface finishes but also the structure to which they are applied must be correctly specified and installed, including necessary time to dry or cure before application of paints or coatings and also including the necessary drying times between each new coat.

Where surfaces meet, it is important to facilitate good cleaning by providing smooth rounded corners and covings. For all biological facilities this should be done where the floors meet the walls and as the complexity of facilities increase this can be required wherever surfaces meet or change direction.

A key part of the design consideration of biological facility surfaces, especially in resource limited settings, is the selection of appropriate materials that can be obtained locally and that meet all of the above requirements; as well as being supported by a local skilled labour force needed to perform the manufacture and or correct installation of all materials to the correct installation standards. Try to avoid specifying and using exotic materials that are imported at high cost and in particular aim to avoid importation of specialist labour to install such exotic materials for which the local skill base to perform subsequent repair and maintenance may be non-existent.

4.4. Furniture

Furniture installed in a biological facility needs to be strong and sturdy to enable safe and reliable use and to ensure a long service life. Furniture can be fixed in position but can also be mobile or moveable to facilitate easier use and cleaning (mobile items will need wheels that can be locked in place). As for the surfaces discussed above to be specified in the facility, furniture is best sourced locally or regionally if possible in order to reduce the overall costs, especially in the context of limited resources. Many materials can be considered in the design of biological facilities and it is important to ensure the qualities and durability meet the requirements of all facility surfaces.

The ability to work on furniture (such as a workbench) without it moving is very important, and the ability to clean the facility furniture after normal use and or in the event of an incident or spillage of biological material is fundamental to safe operation and use. In the design of laboratory furniture simplicity is important as is the avoidance of parts (joints and crevices) which can harbour biological materials. So attention should be paid in careful selection and detailing of furniture. Where possible during the design stage obtain samples of proposed furniture to be used in the facility and agree these are acceptable with the building owner before proceeding to order.

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Many materials are inappropriate for use in a biosafety facility, in particular those which are absorbent and so in the selection of furniture and in particular in the selection of seats, chairs and stools absorbent fabric should be avoided. This extends also to curtains, blinds and carpets all of which are normally prohibited due to the absorbent nature of the material and subsequent difficulty of cleaning, disinfection and decontamination.

There are many laboratory furniture specialists who can provide well designed systems and these are worth considering if available economically and if well supported in the region. It is also useful as indicated previously to carry out research into similar new facilities in the region in order to gain useful insights into existing solutions and experiences. Such benchmarking exercises can be very helpful in the early stages of the design process and such shared experience can be extremely useful both nationally and regionally. Samples can also be tested against chemicals, solvents and heat.

4.5 Fixtures and fittings

By fixtures and fittings we include items like doors and windows as well as fixed devices such as switches, sockets and controls.

Doors need to be designed to meet all of the local building codes including for fire protection and escape. It is very important that doors always include a **vision panel** so that accidents can be avoided when opening or closing the door. Door swings should be designed to facilitate safe opening and closing and to minimise any disturbance to the safe operation of BSCs and other biological safety equipment. Doors need to be selected to meet the requirements for surfaces set out above and should also be large enough to allow passage of equipment needed to be installed into or removed from the facility during its normal life. Ideally doors should close on their own, this can be achieved using commonly available devices which must be correctly set up. Door locking and security arrangements need to be agreed in accordance with risk assessment but most doors should have some form of control to permit only authorised access. Signage is also normally required (see later).

Windows are helpful for daylight and to improve wellbeing in biological facilities. In BSL1 and BSL2 facilities, these can be opened and used also for natural ventilation - so long as this is carefully considered (see below). There should always be insect and arthropod screens fitted and security measures may need to be in place to prevent unauthorised access. As the risk level increases windows will need to be non-opening as discussed in the next part. Solar protection needs to be considered to reduce unwanted heat gain and one-way vision films may need to be added for improved privacy and security as well as the possible addition of films or bars for extra security (some one way films do not work at night). Observation windows are sometimes desirable to allow visual contact between adjacent rooms or are required for personnel safety monitoring from a safe location within the larger facility (to view inside BSL3 from a BSL2, for

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instance). Where such visual access is incomplete or impossible this can be substituted by closed circuit television (CCTV).

Electrical accessories such as **switches, sockets and controls** need to be designed and selected to consider the effective cleaning and disinfection needed, and as the complexity of facilities increases may need to be made to provide a barrier to the movement of air (see sealability in the next chapter). They may also need to be splash resistant or even water tight, especially in larger animal facilities.

4.6. Lighting

Illumination inside biological facilities is very important in order to facilitate safe working and can be made up of two main components: daylighting and artificial lighting. Daylighting can utilise windows and other architectural features but should always be designed to minimise glare and solar gain. Artificial lighting will always be needed and should also be designed to eliminate glare and reflections that can impact on safe working. Lighting levels between 300 and 500 lux are normally deemed acceptable, good colour rendering and a high degree of uniformity will be very important.

Lighting luminaires, as for furniture, fixtures and fittings are best sourced locally where suitable choices are available. They should ideally meet the requirements for surfaces being easy to clean and maintain, the importance of these features increases as the risk level increases and so sealed and water resistant fittings are often used. **Maintenance considerations are important** in the design and selection of facility lighting and agreement should be reached between the client and design teams on how lighting should be maintained, on what frequency and by whom. Lighting should be accessible and where access to maintain lighting may be difficult or strictly controlled for safety reasons the design can include suitable redundancy such that failure of a single lamp or luminaire does not adversely affect lighting levels; this allows enabling effective maintenance intervention to be planned safely.

In addition to daylighting that may be available sometimes and artificial lighting available normally there will be a need for task lighting and also emergency lighting. Task lighting can be added by users based upon need but in some facilities such as a necropsy suite in an animal facility task lighting may need to be specially designed and included in the original design.

Emergency lighting should be designed to allow safe continuation of work until the work can be safely stopped in order to minimise any risk, enhanced emergency lighting levels should be considered to allow such safe stopping of work (minimum code requirements normally allow only for safe egress). Emergency lighting levels and duration need to be agreed between user and design teams. These can be local or central systems or a mixture of both and should be extended to technical areas in order to enable safe emergency maintenance as may be required in a fault, breakdown or other emergency.

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4.7. Ventilation and airflow

Careful consideration and **good design of ventilation and airflow** is essential to the safe functioning of all biological facilities. Two fundamental principles are normally stated in most guidance and sometimes used together or used interchangeably, these are '**inward airflow**' and '**directional airflow**'. They are not always used correctly and can sometimes be misunderstood or confused.

Ventilation can be provided naturally or mechanically or by a mixture of these methods where the biological risk is assessed to be relatively low. However, as the risk level increases then natural ventilation design becomes less reliable and is no longer used, here mechanical systems only are used. Actually, WHO currently recommends that where possible in the planning of new facilities that the provision of mechanical ventilation systems is considered in order to provide an inward flow of air without recirculation. A simple extract fan can provide this function if well designed. Recirculation however is an important consideration especially in areas where extreme climatic conditions prevail and recirculation can contribute to significant energy savings so long as appropriate safeguards are in place (such as HEPA filtration of recirculated air).

Inward airflow should be seen as a requirement ensuring that the net flow of air is always entering the biocontainment facility from adjacent occupied building spaces. This protects the immediate environment outside of the facility from any uncontrolled biological release. In mechanical ventilation systems it is normally achieved by using extract systems only or ensuring a higher rate of extract than supply. Natural ventilation systems, especially using openable windows are unable to guarantee inward airflow as it is difficult to control natural driving forces like wind or buoyancy. For any biological procedures **air should always flow away from the worker, across the work area also taking any potentially infectious materials away from the occupied areas and then outside of the facility** – so if achieved 'naturally' airflow should be 'outward' through an open window.

Directional airflow is a requirement which aims at ensuring ventilation air moves from areas of low or no risk to areas of increased risk. Directional airflow is achievable with natural ventilation as noted above, but care should be taken to ensure its effectiveness at all times and facility users need to understand the limitations offered by such natural ventilation in biological facilities. If suddenly the direction of the natural ventilation is reversed then there can be an adverse impact directly on the safety of the facility worker.

Natural ventilation can generate high ventilation rates and can be economical to design into a facility but it needs to be well managed and fully understood by the users of biological facilities in order for work to be carried out safely. Guidance states directional airflow needs to be assured and to be effective air should move at 0.5m/s (TB Laboratory Biosafety Manual, WHO, 2013).

Below are examples of good and bad natural ventilation, it is obvious that external conditions and wind direction can impact directly on worker safety.

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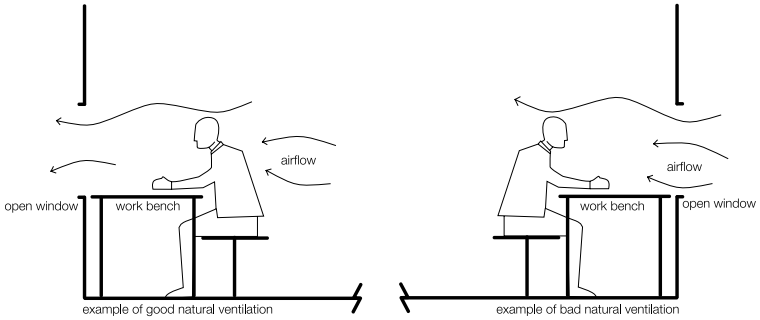

Figure 13. Examples of good and bad natural ventilation

Mechanical ventilation can ensure consistent and continuous directional airflow as well as inward airflow. Below are two examples of mechanical ventilation, the first is hybrid using extract only combined with natural make up ventilation. The second is fully mechanical. It should be noted that the design, selection and positioning of supply air diffusers is critical to good directional airflow. Typically air change rates can be in the region of 6 -12/h.

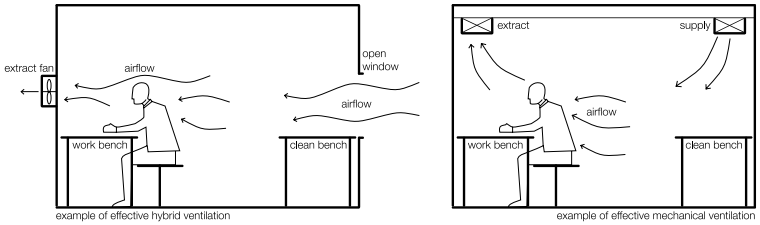

Figure 14. Examples of effective hybrid and mechanical ventilation

4.8. Equipment

Biological facilities will often need to accommodate generic equipment but sometimes the equipment can be quite specialist and large or complex. The most common types of equipment were discussed in chapter 3. It needs to be remembered that in the early design stages, when the user requirements are being formulated, that a comprehensive list of proposed equipment should be drawn up and used to assist in the development of plans and layouts as well as in developing logical and practical people and equipment workflows.

Equipment will need to be admitted to, and potentially removed from, the facility during its planned life and so doors and access routes should be designed to facilitate this as discussed above already. It is important that the structural design of the building and the specification of its floors allow for both the movement and loading of any specialist equipment. It is also important that where known, the correct utilities and services are installed in readiness to allow operation of specialist equipment. Most small autoclaves and standard BSCs can be powered from normal electrical outlets but larger perhaps specialist equipment may need specialist

utility connections such as three phase electrical connections or gas, which if they can be incorporated in the final design will save considerable time, effort and cost later on.

Some equipment may generate heat or require special conditions and some like BSCs will need to be carefully located to ensure their safe operation. This can impact on many other aspects of the design and it is necessary to ensure that the client and design team work closely together to ensure all anticipated requirements are included such as heat extraction, cooling etc.

4.9. Health and Safety

A number of basic systems will need to be included to ensure the appropriate **health, safety and welfare of occupants in a biological facility**. Many of these may be required by local building codes or regulations such as fire detection and alarm systems and other life safety systems. Many others will be much more specific to the activities planned inside the biological facility. They can be determined as part of the biological risk assessment and of a wider facility health and safety risk assessment.

The following systems should be considered and discussed between the client and design teams:

- Fire detection and alarm systems
- Emergency lighting systems
- Emergency power systems
- Emergency shower systems
- Emergency eyewash facilities
- Emergency access and egress
- Emergency evacuation and medevac

First aid is an important aspect of health and safety and it is important to consider how and where first aid may need to be administered. In larger facilities it may be appropriate to include a first aid room but this needs to be evaluated carefully and in addition supplementary first aid equipment, facilities, stations or areas may be needed. The consideration of first aid also needs to establish methods which may be needed to evacuate a medical emergency for which the increasing complexity of facilities and increasing risk levels will warrant careful attention, especially if the casualty becomes potentially contaminated by biological agent during an accident or incident.

Eating and drinking is always prohibited in biological facilities and so ***separate* welfare facilities including staff dining and rest areas should also be included in the facility design**. These should also be the location for the supply of fresh potable drinking water – the drinking water supply should be fully separated from any laboratory supply with no contamination risk. Drinking water services or stations should not be incorporated within the biological facility.

Rest rooms (WC's) need to be considered and located carefully based on the planned occupancy patterns of any facility and normally require staff

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to leave the biosafety facility and use rest rooms located in a safe common area. On occasion it may be necessary to include wash rooms inside a biological facility, this is rare.

4.10. Utilities

The following utilities would normally be included in most biological facilities:

- Water supply
- Drainage
- Electrical supply
- Gas supply

4.10.1. Water supply

Quality and dependability of any water supply in a biological facility is essential. It should be understood as described above that drinking (and eating) is not permitted in any biological facility and that the facility water supply should be fully **separated from sources of drinking water** which must be located outside the facility in a suitable area designed only for eating and drinking. Each biological facility water supply should be fitted with a device to prevent backflow which can take the form of a storage break tank with a suitable air gap or a reduced pressure zone (RPZ) valve. The storage tank has the advantage of providing some capacity during supply failures.

There may also be a need to provide specialist water services inside the biological facility, these might include filtered water, purified or distilled water, de-ionised water or water produced in a reverse osmosis machine. Part of the design process will need to fully establish such user requirements and incorporate the necessary provision, space and utilities for such services.

4.10.2. Drainage

Normally devices using water will also require some form of drainage. Drainage may also be needed for items or machines which have no direct water supply connection. It is important to establish what drainage requirements may be needed during the development of the user requirements; for instance, some analytical machines may produce liquid waste from the analysis of samples or as a by-product of a process. In all cases not only is it important to determine if drainage is needed but also if the drainage can be discharged directly to the public sewer or needs some pre-treatment. For instance a machine analysing blood samples may produce liquid waste that must be collected in a sealed container, possibly pre-filled with disinfectant, this container may then need to be moved through the waste stream for autoclaving or incineration. Space for the container and for its movement all need to be considered as part of the process flow analysis. Fixed drainage systems will need to be complete with syphons and vents and these may need to be designed to

accommodate effects of ventilation systems. Some drainage systems may even require specialist effluent decontamination systems in order to prevent any risk of the contamination of public sewer systems and the venting systems may need to be fitted with specialist filters to prevent release of aerosols.

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4.10.3. Electrical supply

Electricity supplies are essential for the operation of modern biological facilities and in particular to support adequate lighting systems. The **supply should be sized to meet the planned needs** of the facility and may need to incorporate three phase supplies for some equipment. **An emergency power generator or Uninterruptable Power Supply (UPS)** may be needed to ensure safe operation in the event of disturbances or interruptions to the normal power supply. The size and duration of emergency supplies should be designed to meet safety requirements. As a minimum, in the event of a loss of mains power it should be possible to end current working activity and exit the facility safely. This may be satisfied simply by a very small UPS just large enough to allow the continued safe function of a single BSC for say 30 minutes (located at the BSC), along with an appropriately designed emergency lighting pack. Other biological facilities may be designed with 100% back up generation and three days' supply of fuel at full load. Each need should be individually assessed and balanced to meet the biological risk assessment, it may also need to comply with more precise requirements case by case.

4.10.4. Gas supply

Gas is used in many laboratories. This can be natural gas, carbon dioxide, nitrogen and sometimes oxygen along with others. Since gas can be dangerous (as an explosive or asphyxiate) it is very important that the installation is sufficient for the need and is well designed and well maintained. It should comply with national installation standards and is advisable to be equipped with a manual safety system to shut off supplies in the event of an accident. Gas detection or oxygen depletion systems for some gas types may also be needed as leakages can be very dangerous if they pass undetected.

4.11. Security and access

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As part of the biosecurity measures of the facility discussed earlier, it is normal practice to **restrict access** to biological facilities, with access restrictions and constraints increasing proportionately to the increasing risk posed by the biological agents present. When designing biological facilities it is important to establish early during definition of the user requirement specification what **security systems and access controls** are likely to be needed. When considering and evaluating facility security, access procedures and systems, it is important, as with all other aspects of design, to deploy systems and measures that are commonly available

and well supported in the locality of the new facility. The measures considered will also need to match the frequency and capacity of access required; for instance, in a busy hospital access to a central diagnostic facility may be controlled by a reception desk with a permanent staff in place 24/7- responsible for receiving samples, for admitting personnel (access/egress) and also logging all activity, there may also be a signed log book for instance. A small research facility on the other hand may be visited much less frequently, by a limited small group of researchers, each of whom has a unique access code so that their movements are tracked and logged centrally. Equally this small group of researchers could simply sign out a key from the security lodge providing an equal level of tracking but with much less reliance on technology and using manpower instead. Systems can combine physical and electronic security and access controls. Intruder detection systems if included can normally only be set when facilities are unoccupied.

Where increased security risks are determined and/or enhanced access controls are required then each case needs to be fully assessed in order to determine appropriate measures. This may need to be done in partnership with local or national agencies where biological agents pose a potential target. This will be discussed in the next part.

4.12. Signage

It is normally required to identify biological facilities, that is BSL2 and BSL3 facilities, with the **biohazard symbol** in order to differentiate them from other rooms devoid of biological risks. Similarly, inside these facilities, equipment that normally contain hazardous biological materials, such as fridges, freezers, BSCs, incubators, autoclave, etc. should bear a biohazard sign to differentiate them from those that do not (such as fridges that only contain reagents, or an autoclave that is only used for sterilization purposes – e.g., of culture media or solutions, or decontaminated reusable glassware and instruments –, not for waste treatment).

In addition to the international biohazard warning symbol, it will be necessary to include other signs, such as **emergency escape signage**, and **signage for electrical, gas and other installations**. Inclusion or exclusion of special signage in the project scope in addition to mandatory safety signage should be specified in the contract. Clarity here is important since all needed signage will have to be in place before the new facility can be used as originally intended.

4.13. Pest Control

Most guidance proposes that facilities are designed to minimise infestation with rodents and arthropods. For BSL1 and 2 laboratories which are allowed to have openable windows then arthropod proof screens are usually recommended. It is also important to prevent ingress of and possible infestations of rodents and birds as well as insects in the laboratory through all possible routes.

This can be particularly problematic in Southeast Asia where tropical insects can be incredibly skilled at entering buildings by many imaginative routes. In addition there may also be reptiles and mammals which need to be considered such as geckos, snakes and monkeys.

Plants can also become a problem in tropical climates and if allowed to grow in some places can damage exterior waterproofing and lead to problems with ingress of moisture and rain water.

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5. Some advanced design features applicable to containment facilities

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5.1. Separation

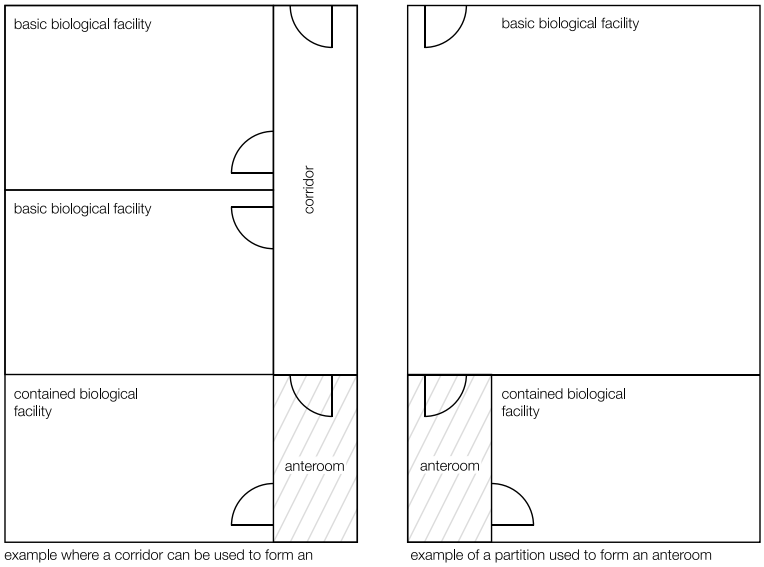
Separating at risk activities from others, as also, if possible, activities of different levels of biological risks separated from each other is generally considered a good practice in order to avoid exposure of non-concerned staff (leading to conducting different activities in different rooms, of different biosafety levels). **At risk activities should be located well away from general circulation areas**, well away from offices, canteens or busy places like lecture rooms and auditoria. Highest risk activities may justify a separate floor or building, with additional safety and security measures.

Placing the higher biosafety level biocontainment facility inside a facility operating at a lower biosafety level, such as a BSL3 laboratory inside a BSL2 suite, is also common and acceptable practice.

Separation can be enhanced by having two sets of entry doors in series, creating a sort of anteroom between for instance a corridor and the contained facility. This can be advised at BSL2 and is a usual feature at BSL3.

The **anteroom** provides a buffer to people flows but also to airflows. Consideration should be given to ensuring this anteroom is correctly sized as it is also normally used as a space for staff to put on special clothing, footwear and Personal Protective Equipment (PPE). There needs to be sufficient space in the anteroom to put on and take off the clothing and PPE as well as additional space to store both the new clean supplies and the used clothing and PPE (before treatment and re-use or disposal). There may also be a (step-over) bench or line to separate the clean and dirty areas. This often dissects the anteroom in two. When available, the anteroom is the best possible place to install a hand wash basin (and possibly a shower, if needed, at BSL3).

Typical arrangements for separation of biological facilities are seen here.



example where a corridor can be used to form an anteroom

example of a partition used to form an anteroom

Figure 15. Examples of arrangement for separation of biological facilities

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Anteroom doors should be used in sequence with only one being open at a time to help improve biological containment. Ideally they will be self-closing and, in higher risk settings, have an electromechanical interlock system with an emergency override facility.

5.2. Access and Security

Separation as detailed above will help to limit the number of people passing close by the facility but it will still be necessary to restrict access only to those persons qualified and authorised to access and use the biological facility. Laboratory access control is one of the compulsory features that need to be included in designing containment laboratories. It is possible to provide many forms of access control as discussed in chapter 4. It is important for higher risk biological agent facilities to create an entry and exit log for facility users which can be manual or automated. If electromechanical door interlocking is provided this can often be integrated with a security and access control system - but where resources are limited it remains perfectly feasible to utilise simple and reliable technology such as logbooks and keys.

For all BSL3 facilities it will be necessary to ensure windows are closed, sealed and break resistant.

5.3. Sealability

Where biological risk assessment determines the requirement for a biological facility to be designed to be sealable for decontamination – such as traditionally BSL3 facilities –, then a clear understanding of what is meant by sealability is needed. There are a number of national guidelines that discuss sealability of biological facilities and there are different methods available for assessing, testing and even measuring the performance of facility sealability.

In this case, if the requirement for sealability is justified by the need to carry out **airborne chemical decontamination**, the degree of sealability should be defined on a risk analysis of the decontamination activity, more especially on the impact of leakage on the efficacy of treatment and also the health and safety of the occupants of the surrounding areas.

The design team, together with the client/user team will need to establish in clear terms what is required and how it should be successfully demonstrated. This should be defined very clearly in the user requirements specification and where possible should **indicate exactly how the sealability will be verified or validated**. This requirement and process should then be incorporated into the design and specification documents and be included also in the building operating and maintenance manuals.

Sealability usually requires that the **complete permanent boundary or envelope of the biological facility is sealed** and that **ventilation ducts can be sealed** for the duration of the decontamination phase of

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the gaseous decontamination cycle. This will include careful detailing of all joints between floors, walls and ceilings as well as the joints around window and door frames. All windows should be sealed closed, but doors may be sealed temporarily by using tape or specially designed seals for the duration of the decontamination phase only.

In addition to **sealing all construction joints**, it is also necessary at BSL3 to seal around all other possible air paths such as joints around **sockets, lights, pipes and barrier equipment** (autoclaves, pass boxes, dunk tanks…) because if not sealed fumigant can escape into other places and so pose a health risk. It is really quite pointless, but common, to find that obvious construction joints are well sealed but services leak very badly. As well as sealing around engineering services it is also necessary to prevent air movement through ducts, conduits, light fittings, sockets and switches etc. This can add significant cost to the construction of a biological facility and will also add large costs to the ongoing maintenance, testing and validation of saleability. This is one reason why BSL3 facilities are traditionally less common and more expensive to both build and to operate.

Where sealability is a requirement careful design optimising the size of the space and minimising penetrations can help simplify construction and testing.

Sealability is important for two reasons: first, escape of gaseous decontamination agents can be harmful and dangerous to facility personnel; second, loss of gaseous decontaminant can reduce efficacy of the decontamination process.

Autoclaves can sometimes be designed to pass material across the biological facility barrier and they will need to be carefully located in accordance with the planned waste material flows. These barrier autoclaves will need to be integrated into the sealed facility boundary using a '**bioseal**'. Bioseals must be integrated into the design carefully to

Figure 16. Barrier autoclave (load side view)

Figure 17. Barrier autoclave (unload side view)

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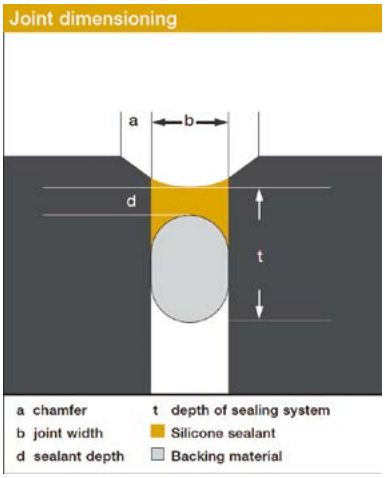

Figure 18. Joint dimensioning (Wacker Sealants - www.wacker.com)

ensure good installation as well as ensuring the possibility of initial and periodic testing. Pictured in Figures 16 & 17 on the previous page is an example of a barrier autoclave in a BSL3 facility seen from both inside and outside of containment.

Achieving sealability in design and construction details can take many forms but the most cost effective is by the use of a designed gap and suitable silicone sealant or mastic. The designed gap allows the incorporation of a (semi-rigid foam) backing rod which supports and enhances the strength of the seal. Preparation is critical, and for this, cleanliness as well as all of the recommended and necessary cleaning and priming will ensure a long lasting and durable seal. A typical detail is found here. Always follow the sealant manufacturer's guidance including careful use of all of the recommended cleaners and primers.

In addition to sealing using traditional sealant materials there are also a number of proprietary products available for sealing pipes, cables and ducts. Such products have their place and can be convenient, flexible and sometimes quite easy to test. Proprietary sealing solutions can sometimes add cost to projects and need to be considered in the context of local resources including skilled labour. Whatever solutions are finally used, early mock up and testing will help to agree standards of the finished work.

5.4. Ventilation and airflow

Combined with the need for closed and sealed windows, BSL3 facilities normally require **controlled ventilation systems** designed to maintain a reliable 'inward airflow' to the facility. This net inward airflow is normally assured by **maintaining the facility at a reduced air pressure which is negative to the surrounding rooms and facility exterior**. This is normally achieved by extracting more air than is supplied. It is common for the room pressure or room differential pressure to be measured and displayed outside the facility entrance but it should be visible (separately as needed) also inside the facility to demonstrate continued function and presence of the required inward airflow, it may also be fitted with an alarm indication (using sounds/lights or both).

Air extracted from the facility may be HEPA filtered depending on the outcome of a risk assessment. When extract air is HEPA filtered it can be discharged or it can be recirculated in the same room. Recirculation of the air should be done only if there is no additional risk of recirculating

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volatile toxic solvent or chemical (which would pass through a HEPA filter). Where necessary separate extract only routes can be provided for the needs of local exhaust ventilation for harmful fumes.

HEPA filters need to be carefully installed, and their housing correctly designed, in order to ensure they can be decontaminated by gaseous methods and periodically tested. HEPA filters are tested after manufacture and arrive with unique certificates but this testing must be repeated after installation on site. Testing of **HEPA filters** usually happens after they are installed in their housing and so great care is needed in **ensuring that testing (or validation) 'in-situ' can be completed effectively, reliably and with good repeatability**. Testing usually involves operating the ventilation system 'normally' and injecting test smoke into the duct some distance upstream of the filter and then measuring smoke concentrations both upstream and downstream of the filter. Injection and test ports must be strategically placed in order to ensure a correct full challenge and good measurements in all positions. HEPA filter testing is most often completed manually. HEPA filter testing is skilled work requiring trained qualified people and specialised testing devices which must be maintained and calibrated regularly.

Establishing inward airflow to a biological facility does not by itself ensure safety of the facility staff. In addition to inward airflow, directional airflow must also be designed so that air moves always from areas of no or low risk to areas of increasing or high risk. Careful selection and positioning of the air terminal devices forming part of any heating, ventilation and air conditioning system (HVAC) will help ensure its design meets directional airflow needs. In the simplified example below both inward airflow and directional airflow are indicated.

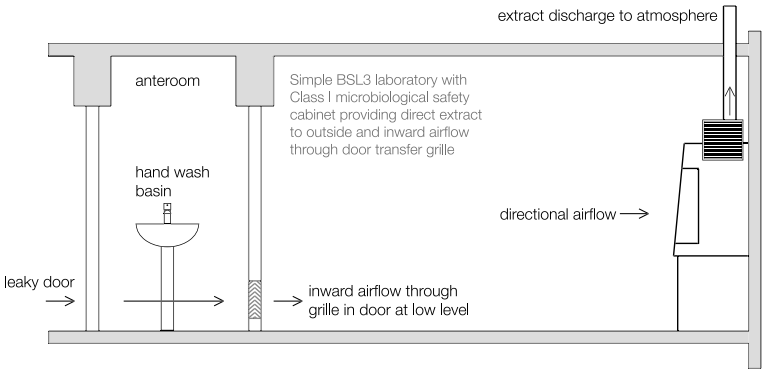

Figure 19. BSL3 Ventilation and airflow example

Air is extracted via a BSC creating directional airflow and air induced by the negative room pressure provides inward airflow through a leaky outer anteroom door and a designed grill or valve in the inner door.

It is important always to consider the velocity and direction of all air supplied into the biological facility room and to ensure it does not impact adversely on safety, in particular disturbing the proper functioning of the

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BSCs, (as well as the comfort of the users). This is true also for any air recirculated inside the room, for instance by local air-conditioning units.

Below are two actual examples of situations where the ventilation design may not have allowed for the final (later) positioning of the BSCs. The first illustrates a wall-mounted air conditioning unit, these units can generate high velocity airflows which can also change direction due to oscillating blades. The unit is mounted very close to, and perpendicular to, a BSC. It is highly likely that the protection from the BSC would be adversely affected by the airflow from the wall unit. In the second example, the air supply grilles of the fixed heating ventilation and air conditioning (HVAC) system had to be partially blocked to minimise impact of airflows on the BSC inflow.

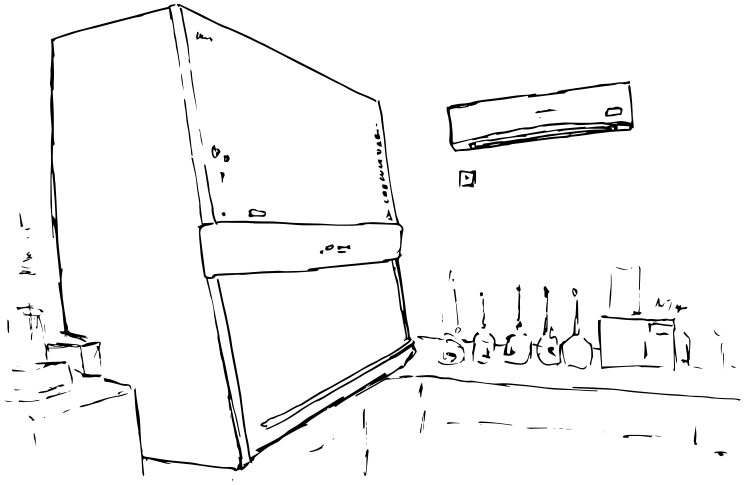

Figure 20. Ventilation: possible impact on safe BSC operation (Example 1)

Figure 21. Ventilation: possible impact on safe BSC operation (Example 2)

5.5. Drainage

Drainage systems may also require additional devices and equipment as the biological facility increases in risk. Deeper syphons may be needed due to the increased negative pressures maintained in the facility. It may be necessary to add filtration to the vent pipes.

Also it may sometimes be necessary to **treat the effluent** before discharging it to the public sewer. This can be done in many different ways, depending on the nature and volume of the effluents. In the most critical cases and for large volumes, **Effluent Decontamination Systems (EDS)** or "kill tanks" may be justified. There are different types of EDS (thermal or chemical, continuous or batch), which exist in different sizes and with different control systems. The type and sizes are dictated by the volume and flow rate of effluent to be treated, they can be as small as a sink unit (but in this case there are usually much less expensive treatment options available) or very large needing their own building.

Deciding when to include an EDS needs to be based on sound biological risk assessment, also taking into consideration that this type of equipment is difficult and expensive to operate, control and maintain, and is generally subject to technical issues and difficulties. And if the decision to install an EDS is taken, there needs to be a detailed study on the type of effluent and a calculation of the normal and peak flow rates to help quantify the load. Once this is completed decisions can be taken on the most appropriate type of system thermal or chemical, batch or continuous. These decisions will require very specialist input which is far beyond the scope of this introductory booklet.

5.6. PPE & procedures

Increasing levels of biological risk may require **enhanced PPE and procedures**. It is important in designing facilities that these additional requirements are conveyed from the client/user team to the design team as very often space for the storage of, and, for the donning and doffing of additional PPE or for carrying out enhanced procedures may be required to be included in the designer's plans. Space cannot be created later.

As well as correctly located and adequate storage space for PPE and consumables it may also be necessary to charge battery operated respiratory protective equipment (RPE). This will also need additional space and might include special shelving systems for equipment storage and integrated or separate dedicated battery charging stations.

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6. Challenges in the design, construction of biosafety laboratories

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During the first DET training workshop a number of group exercises considered the combined experience of the DET and discussed typical challenges faced during the design, construction, operation, maintenance and management of biosafety laboratory facilities. Many of the issues identified were not unique and are in fact a universal and shared experience regardless of national wealth or apparent technical advancement. They can be grouped in many ways, but it has been decided to present them here in the order of a typical project pathway, starting with the earliest phase (the phase often happening even before a design team joins the process).

The separation presented below is somewhat artificial and in fact the processes involved are far more complex and interrelated than is possible to distil into such simple groupings. Peeling paint from a wall for instance can be attributable to poor design (poor selection and/or poor specification of the paint) but it can also happen where the specifications and design are correct and instead the problem can be attributable to poor preparation of the subsurface, insufficient drying time before application or between coats, poor application or mixing of the coating, poor construction, poor supervision and/or lack of sufficient quality control. Also, an incomplete user requirement specification could also lead to such a problem – for example if a particular planned chemical cleaning regime or decontamination method was omitted in the user requirement specification but then used without consideration of the consequences in the finished building. So the lists below, even though grouped under a convenient project phase heading, illustrate issues that need often to be addressed during each sequential project phase – most however do originate in poor design or specification.

6.1. Challenges of the USER'S REQUIREMENT phase

During this phase, the idea of what is needed to be built or modified is first proposed. It may be in answer to a very specific or more general organisational, national, or even international need and may be expressed quite simply at first, for instance: "we would like to develop a national BSL3 laboratory capacity", or "we would like to have a basic laboratory to conduct safely this or that type of diagnostic or research work". However, these aspirations alone, justified or not, are incomplete – it is impossible to say to a designer or builder "we need a BSL3 lab" or "we need a basic research lab" – since there are very few or very limited 'standard models' and very few such laboratories are the same, with most being quite unique and quite specific. For each new laboratory facility there should be a clear need supported by sound biological risk assessment as described in section 1.4.

Risk assessment needs to be focused on the projected activities, also taking into consideration the context, the organisational and logistic aspects, and the capabilities (including a possible lack of resources). The problem is that this is often not done, and that risk assessment is disconnected from reality.

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We consider here as general biosafety reference for conceiving a new general laboratory facility the current edition of the WHO **Laboratory Biosafety Manual** (2004), because it has been developed with a particular concern for the development of laboratory capacity in low resource countries. It provides in the first 20 pages some clear guidance on 'general principles', 'biological risk assessment' and 'laboratory design and facilities'. For more specific types of facilities dealing with TB, there is a more recent (2012) WHO **Tuberculosis Laboratory Biosafety Manual**. It does not mention biosafety levels (BSL) and instead uses a structure considering low-risk, moderate-risk and high-risk TB Laboratories, which are evaluated on the basis of the work planned to be undertaken and addresses design features needed to mitigate those specific and increasing levels of risk. The **risk-based approach** used in the TB manual is probably closer to what might be expected for the new, more general WHO **Laboratory Biosafety Manual** due to be published in 2018.

To develop the concept of each and every new facility, it is fundamental to fully understand the purpose intended and the detailed nature of the activities, and to conduct a rigorous biological risk assessment. This is the object of the 'client brief' and 'user requirements specification (URS)', based upon the operational needs and the biological risk assessment.

6.2. Challenges present during the CONCEPT phase

The following section identifies two common issues that need to be tackled as soon as possible during the concept phase, given their impact on the whole project and the successful completion a new biosafety facility.

Budget

It is very important that during the concept stage a **realistic and conservative budget estimate** is established so that sufficient funding is allocated for the complete construction project, as well as possibly all other costs associated with the new facility. Total project costs must consider all project-related **direct costs**, **indirect costs** and should also ideally include an appropriate **contingency** (to cover unexpected costs). Contingencies can for instance be fixed at 5% of the estimated project costs. **Operating costs** will need to be considered as will **relocation and start-up costs**.

Programme planning

Directly related to the budget is the programme planning. **Planning needs to be realistic and consider the complete process**, including for instance necessary allowances for the commissioning and start-up phases, and also include some contingency (in this case to cover possible unexpected delays). Errors in the planning can lead to increased costs, which in turn may impact the budget. Errors in planning and

compression of programmes later in the project can have dramatic consequences on quality.

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6.3. Challenges faced during the DESIGN phase

The term 'design phase' is actually misleading and quite simplistic, in fact it covers several project stages including the separated **'concept', 'developed' and 'technical' design stages** (as detailed in the RIBA plan of work[11]). However for the purposes of this section there are a number of challenges that can significantly affect project outcomes during the whole of the design phase. Most problems can be avoided by good design and specification.

6.3.1. Experience

Lack of experience in the owner, designer or builder team is not unusual since designing new biosafety laboratories is not a very common activity. Inappropriate experience can possibly also be a significant issue.

There can also be an issue related to experience when concepts, ideas and technical solutions are imported from a different location - be it in the same region or form very far away – or context, without realising the need for significant **review and adaptation to local conditions** (such as climate, or culture and ways of working) **and capabilities** (such as technical skills, available materials, operational means…). This can result in expensive, unsustainable and unmaintainable solutions.

As an example, use of techniques adapted to climatic conditions that are different from the local climatic conditions, without considering the issue, is likely to result in air conditioning units that are not dimensioned correctly, and to generate problems of condensation, humidity, mould development or pest proliferation.

6.3.2. Poor design; and poor construction and engineering specifications

A number of issues are related to poor design and poor specification during the design phase. These can be attributed to a failure of the owner to provide adequate brief and users requirements to the designer, or to some failure of the designer in interpreting the user's needs and translating them into inappropriate design solutions and specifications. The following list gathers such issues that can be a **direct consequence of**

[11] The RIBA Plan of Work is published by the Royal Institute of British Architects (RIBA). It was originally launched in 1963 as a fold out sheet that illustrated the roles of participants in design and construction in a simple matrix format. The first detailed plan of work was published in 1964. Split into a number of key project stages, the RIBA Plan of Work provides a shared framework for design and construction that offers both a process map and a management tool. www.ribaplanofwork.com

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poor design and/or poor construction specifications and/or poor engineering specifications:

- Inappropriate location
- Over complication
- Missing or inappropriate important elements, such as hand wash basin, basin too small, badly located or wrong type of taps installed (hand operated - when elbow, knee or foot operated would be better)
- Lack of provision of water supplies to hand wash basins
- Incorrectly located or poorly located drainage for wash hand basis basins, sinks or other equipment
- Draughts from openable windows
- Poor laboratory/facility spatial design
- Poor layout and workflows
- Poor personnel and material flows
- Insufficient working space, resulting in overcrowding
- Poor ergonomics
- Lack of write up space (or not separated from working areas)
- Lack of storage space (or not separated from working areas)
- Impossibility to move equipment in (or out) of facility (doors too small)
- Poor or inappropriate specifications (systems and components)
- Poor selection and poor compatibility (equipment/materials)
- Poorly positioned outlets for electrical and piped services
- Lack of appropriate electrical outlets and utility distribution points
- Lack of support facilities (washrooms, rest room, dining room, offices)
- Poor location of safety cabinets and other primary containment equipment
- Poor engineering design
- Limitations of technical space for plant and equipment access and accessibility for good and safe maintenance
- Poor lighting and poor ventilation (both in the laboratories and/or supporting technical spaces)
- Rainwater ingress, flooding of rainwater services and/ or failures of flat roofs
- Condensation including interstitial condensation in materials (due to lack of understanding about climatic challenges, humidity and the significant contrast between indoor and outdoor design condition)
- Undesirable airflows from room fans or air conditioners
- Severe access restrictions to maintain plant and equipment (no planning)
- Poor availability of spare parts and components (equipment selection)
- Difficulty to access and maintain drainage systems (consider access panels and ensure appropriate inspection and rodding/cleaning access)
- Difficulty to access services above ceilings and in ceiling voids (consider access panels designed to match ceiling system with indication

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of purpose of access panel and services to which the panel gives access)
- Poor selection (type) or location of ventilation terminals where central HVAC included
- Impossibility to ensure an airtight placement of the HEPA filters where used (due to poor design or realisation of the housing)
- Inability to decontaminate or test HEPA filters and housings if used
- Poor access to maintain laboratory services and equipment including autoclaves
- Overcrowded and/or inaccessible plantrooms
- Poorly lit and ventilated plantrooms (too dark and/ or too hot to work)

6.4. Challenges faced during the CONSTRUCTION phase

Construction encompasses many aspects and may begin with site clearance and the digging and preparation of foundations. As the construction project progresses there will be a main structure and substructure completed along with a roof, followed by the addition of substrates and eventually the application of finishes. In parallel, activities to install various engineering services will take place and many separate trades will work together (or compete!) to install their various specific and sometimes quite **specialised systems**.

A number of problems can issue from bad construction techniques or defects when applying the planned construction techniques. Examples of such common problems, which can be prevented by attentive quality control, including on details, during the whole construction phase, are given below.

6.4.1. Common issues related to finishes

The following issues are issues that can be due to poor **workmanship** (due to a lack of basic skills and competence, or carelessness), poor availability of **quality materials**, and/or be the consequence of poor **design and technical specifications**:

- Lifting of floor tiles
- Bubbling of floor coverings
- Cracking or separation where surfaces meet (walls, floor, ceiling)
- Cracking at joints in different substrate materials
- Cracking at structural joints
- Cracking around openings of doors and windows
- Missing joints (e.g., grouting missing from tiled joints) or mastic
- Peeling paints (efflorescence and similar problems)
- Sealability problems (see below), including failures where mastic is applied to a poorly prepared surface (it is important to use correct cleaners and primers in accordance with manufacturers' instructions).

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Figure 22. Example of incomplete joints

Sealability issues are one area where experience and best practice can help, and Fig. 22 shows typical signs of sealability problems which normally show quite soon during the early operation of biological facilities (when operating at negative pressure). Dust trails are quite distinctive and can often be can be seen where materials meet at incomplete joints (similar evidence can be seen at penetrations).

6.4.2. Common issues with engineering services

The engineering services must be realised correctly in order to avoid:

- Poor installation of engineering services systems and components
- Poor commissioning of engineering services systems and components
- Poor validation especially problems to validate the BSCs (multiple causes are possible)
- Leaks and Floods caused by poor workmanship, insufficient quality controls and testing, bad contractor re-design or poor material selection
- Condensation problems associated with cold piping or cold ventilation ducting not correctly insulated or vapour sealed
- Noise caused by poorly sited and poorly fixed equipment
- Glare and bad lighting due to poor installation
- Poor commissioning of mechanical ventilation systems and HVAC
- Damage during construction especially in very compact technical areas where climbing over or under systems is made necessary

6.5. Challenges faced during COMMISSIONING and VALIDATION

Commissioning and validation is normally seen as part of the 'construction phase' of a project. It is very important that it is allocated the

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correct amount of time on the project programme, and then that the time allocated is defended fiercely against typical construction and other delays that threaten to compress it. If it is not correctly respected or well managed the commissioning will be rushed or incomplete, leading to ongoing problems often remaining long after the building is handed over.

For this reason on more complex projects it is recommended that an individual or **team** be put in charge of **supervising the commissioning and validation**, they should be directly employed by the owner and act on the owners behalf. The earlier they are employed the better, and they should produce a **commissioning and validation plan** which will include the verification of each design stage and also agreement of the expanded commissioning and validation programme. The individual or team should also be responsible for ensuring that all of the needed documentation is in place and approved before handover. For smaller projects it remains critical that at least one person with the relevant knowledge and experience is responsible for ensuring all of the expected (specified) project documentation is complete and correct before final handover is considered.

During the whole of the construction phase but especially during the commissioning and validation phase it is very important to ensure good quality control – a useful example is illustrated below.

6.5.1. Quality control

Quality controls as noted several times in this booklet are fundamental, and Fig. 23 is an example where systematic checking and testing may not have been as thorough as needed to prevent a possible future drain blockage.

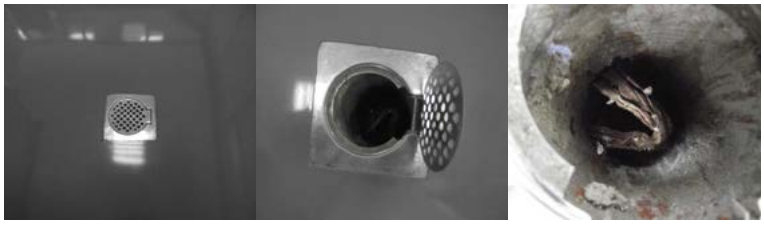

Figure 23. Example of possible drainage blocking scenario

The sequence of pictures above show a floor drain, when closed in the first picture nothing is obvious and facility users would not envisage a problem. If opened as in the second image still nothing is immediately obvious to see. However closer inspection reveals construction debris which if not removed could lead to blockage and possible flooding if and when the drain was ever needed to operate in the event of a major spill or leak. So quality controls must be very thorough and all testing and inspection complete – especially in places that are not immediately obvious. It always pays to look for likely problems hidden from common view.

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6.6. Challenges faced during the HANDOVER phase

Handover is a very critical milestone in a project and is where **responsibility moves from the builder to the owner** and after which point effecting the completion of any incomplete or remaining works becomes significantly more challenging.

As well as all of the work being complete and approved, it is also necessary that all documentation including for all of the testing, commissioning and validation is in place; together with completed operating and maintenance information in a building maintenance manual. Part of the duty of the person(s) responsible for commissioning and validation approval will need to approve all of this important documentation which should as needed be built into the commissioning and validation plan requirements. The following as a minimum should be checked and certified as fully complete and accurate in accordance with the detailed design and specification documents - before any approval of the final building being handed handover.

6.6.1. Basic checklist for handover

- Structure and foundations – all needed 'sign offs' for the construction phase before covering up
- Superstructure - all needed 'sign offs' for the construction phase before covering up
- Finishes - all needed 'sign offs' for the construction phase including any specified tests or approvals
- Engineering Services – completeness of all installations, inspections before covering up, all testing and commissioning data signed off (independent witness)
- Validation – all systems requiring validation are completed and signed off (independent witness)
- Operating and Maintenance instructions – signed off (including ideally by the person in charge of maintenance or their representative if existing)

Obtaining this documentation, especially complete and appropriate **Operating and Maintenance instructions** can be something of a challenge but it needs to be done well before final handover. Obtaining it after handover is always far more challenging.

6.6.2. Start-up phase

Between handover and operation there can also be a start-up phase, this may include **trial running of systems and equipment** and may be supported by the builder and include ongoing maintenance depending on the type of contract. This part is project specific and again lies ouside of the scope of this introduvctory booklet.