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FEASIBILITY STUDY OF EXPANDABLE MOBILE BSL-3 LABORATORY CONCEPT (EMLAB)

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Abstract - Medical service accessibility has always been a concerning problem among the community of inner Sabah region, in Malaysia and many more places around the world. To make medical diagnostic service more accessible, this paper proposes Expandable Mobile BSL-3 Laboratory (EMLAB) as a technological relief measure. The objective of this paper is review and evaluate the feasibility of EMLAB in terms of concept practicality and design consideration. EMLAB is a mobile laboratory in a form of an expandable mobile building structure compliant to BSL-3 and ISO Cleanroom standards. The rationale behind the design of EMLAB was the lack of workspace in existing mobile BSL-3 laboratory for optimum workflow and overall laboratory functionality. One of the vital functions of EMLAB is to address the space issue with an expansion mechanism along with a novel bellow shape foldable seal joint to maintain structurally airtight. The proposed virtue model study can achieve almost 3 times expansion of the initial 10-meter squares floor area making it comfortable for laboratory personal to work. With the use of a novel bellow shaped foldable seal joint, the BSL-3 and clean room standard with negative air pressure are highly achievable. A layout with projected equipment for the proposed study shown the expandable mobile BSL-3 laboratory is highly feasible and practical.

Keywords - Mobile Laboratory, Medical Accessibility, Rural Sabah, Technology Assessment

I. INTRODUCTION

In Sabah, medical service accessibility has been a persistent issue within the community from inner Sabah region. Underdeveloped medical infrastructure and geographic constraints have made quality medical services less reachable to the underprivileged community. In 2002, Kam Agong [1], a mother from Long Semadoh in rural Sarawak, died due to primary and secondary postpartum hemorrhage after giving birth by C-Sections in the nearest maternity facility located 5 hours away. This incident has since sparked the nation's attention on the desperate need of quality medical service and the dire consequences caused by geographical barrier. According to National Health and Morbidity Survey [2], the mean travel time to nearest outpatient healthcare facilities in Sabah is almost double that of Peninsular Malaysia. Given the highest utilization of out-patient healthcare in the state, 80.3% of the rural community stays more than 5 kilometers from the nearest out-patient healthcare facilities. These conditions can be more detrimental in the mist of pandemic outbreak such as Coronaviruses and Tuberculosis (TB). Between 2012 to 2018, there were 33,193 cases of TB cases detected in Sabah which equates to 20% of Malaysia's total TB cases [3]. The delays on TB treatment plays a major factor in addressing the TB pandemic [4]. Dated 20th October 2020, the Sabah Covid-19 labs were reported to be overwhelmed with large numbers of swab test samples from 3rd wave COVID-19 outbreak [5]. It is so severe that a portion of test samples had to be sent to laboratory in peninsula Malaysia to relieve the workload. Public health experts pointed out the lack of proper road system hinders government's effort in coping the virus infection chain. Dated 5th October 2020, there are 3 authorized Covid-19 laboratories in Sabah which all of it are in Kota Kinabalu, the capital of state. A big portions of swab test samples from other districts such as Tawau and Sandakan are sent to these laboratories for the test reagent and equipment. Long travel distance and incomplete road infrastructure render the process inefficient and time consuming. Hence, a solution that provide both infrastructure and geographical conveniences is needed in addressing the problem. This paper sought to propose Expandable Mobile BSL-3 laboratory (EMLAB) as a technology intervention. This paper will be focused on study of technology development and feasibility study of expandable mobile BSL-3 laboratory. Lastly, description of EMLAB design proposition will be explained.

II. EXPANDABLE MOBILE BSL-3 LABORATORY (EMLAB)

This chapter focuses on defining the purpose of EMLAB. This covers the concept, origin of inspiration as well as the background study leading to the development of EMLAB.

2.1 Definition

EMLAB is a laboratory which are (i) transportable, (ii) expandable in internal volume, and (iii) compliant to Biological-Safety-Level (BSL) 3 and ISO cleanroom standard.

2.2 Concept Origin

One of the problems commonly associated with medical outreach program is the lack of good medical practice environment and appropriate equipment [6].

So, engineers and architects have come up with ideas to adapt medical building features into a vehicular structure. In 2004, a mobile health clinic was deployed to study immigrant women's experience on mobile clinic services. The result finds the medical services to be more accessible as the services was delivered within their reach [7]. A similar study on evaluation of mobile clinics shows 25% of respondents continue to visit mobile clinics due to the conveniences. Over 10% of the clients reported that they were not able to receive medical services due to transportation problem. So, in Malaysia, vehicular medical unit such as Mobile Dental Clinic, Mobile X-Ray bus, Flying Doctor Program have been introduced to reach more citizen in need. It is acknowledged that it is feasible to improving medical accessibility through adopting a mobile structure.

EMLAB is an improved adaptation of BSL-3 laboratory in a transportable structure. There have been several versions of mobile BSL-3 laboratory in form of shipping container or vehicles. Studies has proven that these products have successfully improved service accessibility through removing geographical barriers. Despite the service provided has been more reachable, it is not as complete and as effective as a static laboratory due to the scarcity of space and equipment. A mobile building structure that can provide sufficient space is needed to house more equipment and carry out effective workflow. In recent years, revolutionary building design such as transformable building, low energy building and modular building are on the rise due to high environmental awareness. These causes a significant paradigm shift in material selections, design considerations and even in manufacturing process. Hence, the need of space and energy efficient building structure give birth to the design concept of EMLAB.

The main purpose of EMLAB is to provide a building envelope that is transportable, has sufficient space for optimum laboratory operation, and specifically designed for BSL-3 laboratory application. Like others mobile laboratory, EMLAB aimed to tackle medical accessibility issue through bringing more comprehensive services to the doorstep of the underprivileged community. To achieve this, there are three considerations which need to be address during design phase which are (i) how to make the laboratory facility transportable, (ii) how to increase the space and (iii) how to effectively fit in laboratory functions into the building. As mentioned, adaptation of laboratory facility in transportable structure has proven to be a viable solution. EMLAB proposes the use of mobile building enclosure to facilitate the laboratory operation. Then, the entire building enclosure will be dissected into multiple independent subassemblies to be developed separately. In conjunction with it, a kinetic mechanism will be included to allow the building structure to undergo volumetric expansion. BSL-3 and ISO Cleanroom standard will be considered during the development process of the building enclosure.

2.3 The Use of Mobile Building

Mobile building is a form of modular building that can be transported as a whole unit. An important feature of mobile building is that it emphasizes the use of a steel-framed structure as load-bearing element. As opposed to hybrid steel-concrete material that is typically used in conventionally constructed building, the intensive use of steel reduces unnecessary dead load of the building while retaining desired load-bearing capacity and structural mobility. These strengths play an important role in providing a stronger mobile shelter for delicate application like mobile laboratory in this context.

Figure 1: Construction of huoshenshan and leishenshan hospitals in Wuhan, China
Source: http://www.gov.cn/xinwen/2020-02/02/content_5473790.htm#1

From a manufacturing perspective, the production of mobile building is based on product development technique called modular architecture. The building structure is divided into independent elements to be manufactured separately without affecting other corresponding component [8]. In terms of efficiency, what makes modular building a ideal option are streamlined manufacturing process, lower cost and time [9]. The manufacturing process of mobile building reduces the need of repetitive designing process from ground which can be very burdening for big products, simultaneously reducing any relevant cost and waste induced. According to a comparative study between modular building and traditional building by [10], there are substantial waste reduction in material of modular building over traditional building as much as 81.25%. Subsequently, it is 24% more energy saving, which 14% is due to high quality control and waste reduction. Modular building was estimated to be 60% more timing saving compared to conventional building [11]. The construction time of a hospital at Kingston-Upon-Thames, London was reduced from 35 weeks to 19 weeks and 7% potential saving on site preliminaries due to faster build time [12]. These traits can be crucial in the most recent examples were the construction of Huoshenshan and Leishenshan Covid-19 hospitals in Wuhan, China.

The Chinese government constructed and commissioned two emergency specialty field-hospital with an area of 33.9 thousand square feet under 10 days. To achieve this, the entire hospital is constructed with steel-framed structure which was prefabricated off-site and reduce the use of concrete that need relatively longer curing time. The traits of modular building are the contributing factor to the success of the projects. Fig. 1 shows the construction of Huoshenshan and Leishenshan Covid-19 hospitals [13].

2.4 The Expandable Structure

The intention on incorporating expansion mechanism was to provide space through attentive engineering design and architectural planning. The reason EMLAB features an expansion mechanism in design because of the limited space in existing mobile laboratory. Space plays an important factor as it directly affects the useability, working efficiency and user satisfaction. It is always desirable to have a bigger space as more services and equipment can be included within the facility. In mobile clinic applications, a frequent comment among the doctors in using is that they would appreciate more spaces to provide a better quality health services [14]. Certain medical services such as X-Ray requires specific room setting, and the equipment can take up a big portion of the space. This leaves medical workers with little to no space to undergo effective medical service within mobile vehicular unit. The lack of space affected patient satisfaction against the reliability of mobile health unit. A respondent stated out the claustrophobic feel of a campervan and prefer services to be provided in a wider space. Another respondent pointed out that the privacy could be compromised due to room design despite the medical service providers effort in making providing private space [15]. So, it can be deduced that the scarcity of space also posts a similar impact on laboratory application. Given that having a bigger sized building enclosure will reduce its transportability, the inclusion of expansion mechanism allows the building structure to retain its initial dimension at retracted state while provide additional space upon deployment.

2.5 Biological Safety Level (BSL) and ISO Cleanroom Standard

EMLAB will be compliant to both BSL-3 and ISO Cleanroom standards. Biological safety level refers to a series of standards and requirements in carrying out pathogenic related activities within delegated biological lab. This standard requirement is released by the World Health Organization in carrying out pathogenic-related activities within delegated biological lab. The laboratory manual covers several scopes such as microbiological risk level, nature of the work conducted, and laboratory design. The summary of biosafety level in relation to risk groups and permissible work scope are stated in the Table 1[16].

Risk Group	Infection Risk Level	Minimum Biosafety Level	Laboratory Type
1	No or low individual and community risk	Basic – Biosafety Level 1	Basic teaching, research
2	Moderate individual risk, low community risk	Basic – Biosafety Level 2	Primary health service, diagnostic service, research
3	High individual risk, low community risk	Containment – Biosafety Level 3	Special diagnostic service, research
4	High individual risk and high community risk	Maximum Containment – Biosafety Level 4	Dangerous pathogen units

Table 1 : Biosafety level requirement associated with risk group

Biosafety Level 3 – The containment laboratory is designed to process up to Risk Group 3 pathogen and with large quantity or high concentration of Risk Group 2 pathogen that are airborne infectious. The significance of biosafety level 3 is the inclusion of containment features to prevent accidental release of high-risk airborne pathogens to working personnel and the surrounding. These give researchers the clearance on researching not only COVID-19 but also other contagious airborne pathogens such as Ebola Virus Disease (EVD),

ISO Cleanroom standards refer to a set of classification of room based on the cleanliness of internal room air [17]. While it does not necessarily associate with BSL standards, both BSL and ISO cleanroom standards are often taken into consideration in design of containment laboratory. Biosafety level is a set of regulations to prevent viral exposure against working personnel and environment while ISO classification protects sensitive samples and processes from contamination inside cleanroom. ISO Cleanroom standards covers the requirement such as air movement control, permissible air particle concentration, construction material and method etc.

III. TECHNICAL ASSESSMENT

In this study, technical assessment on existing product and technology is conducted to identify the pros and cons of existing products. The assessment will be focused on three main criteria which are (i) space, (ii) mode of transport and (iii) biosafety level.

These factors are closely related to spatial efficiency, transportability, and laboratory functionality. There are limited numbers of mobile laboratory available in the market. These mobile laboratories mainly utilize the inherent mobility of the vehicular chassis and a steel-framed enclosure as laboratory compartment.

Figure 2 : MLEE 4000 DC Mobile Laboratory
Source: http://orlandomedsys.com/mobilabs.html

3.1 MLEE-4000 DC (Orlando System LLC.)

Error! Reference source not found. shows the exterior view and blueprint of the MLEE4000DC mobile laboratory [18]. This product is a BSL-3 compliant caravan-type vehicular laboratory with the laboratory compartment permanently mounted on a 4-wheel trailer chassis (Mercedes Sprinter Turbo Diesel DOKA 411/ Fords-550 Turbodiesel). The compartment is roughly 4m (length) x 2m (width) and weighed 2000 – 3000kg gross weight. The lab compartment is compactly installed with important systems such as double Bio-HEPA filtration system, power generators, and even communication systems. However, the main drawback of the design is that there is a lack of workspace within the laboratory. It can only fit in smaller size and limited numbers of laboratory equipment like autoclave, medical refrigerator, and biological safety cabinet *(BSC)*. Based on the blueprint released, the walking floor area available within the laboratory testing area is approximately 1m x 2 m which can only accommodate up to maximum 2 laboratory personnel only. The entire laboratory workload capacity is suitable for small scale operation only.

Figure 3 : Certek ReadyPOD Mobile Laboratory
Source: https://certek-usa.com/products/laboratories/readypod/

3.2 Certek ReadyPOD (Certek USA)

Error! Reference source not found. shows a trailer-mounted mobile laboratory by Certek US [19]. Certek ReadyPOD is a self-sustainable container-type mobile BSL-3 laboratory. Like ML4000DC, it comes with power generation system, Heating, Ventilating and Air Conditioning (HVAC) system, and plumbing system. The laboratory structure comes in several sizes based on ISO standardized shipping container dimension (20ft, 40ft, 45ft and 53ft). This product inherits the benefits like the fundamental structural strength and mobility from a shipping container. Shipping container is made with weathering steel which are highly durable for extreme condition. It is also detachable from the truck hauler and these advantages could be beneficial for long term deployment purpose. The available working space for a 40ft mobile laboratory is 2.1m x 10.3m. Compare to ML4000DC, it has a bigger workspace which allows more functions, working personnel and bigger equipment to be added into the laboratory for higher capacity workload.

3.3 Mobile Biosafety Level 3 (MBSL-3) Laboratory (China)

In 2014, China deployed an MBSL-3 laboratory shown in **Error! Reference source not found.** to help addressing Ebola Virus Disease (EVD) epidemic in Sierra Leone [20], [21]. Similar to Certek ReadyPOD, MBSL-3 Lab was modified from three shipping containers comprises of a main BSL-3 laboratory module, auxiliary module for cleaning and tech support, and a command center module. The BSL-3 laboratory module and auxiliary module are connected through a corridor which are sealable and retractable. The laboratory module dimension is 9.1m (length) x 2.4m (width) x 2.9m (height) which are subdivided into separated operating rooms.

Figure 4: Mobile Biosafety Level 3 Laboratory deployed in Sierra Leone
Source: http://cocorioko.net/china-blesses-sierra-leone-with-mobile-bio-safety-laboratory/

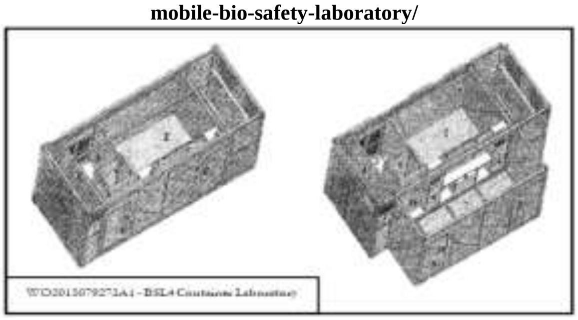

Figure 5 : BSL-4 container patent that uses telescopic mechanism for expansion operation

Source: Patent No. WO2015079273A1(2015)

Despite the structure is not expandable, the design optimizes the spatial utility through proper placement of essential and auxiliary functions to be integrated into a complete mobile BSL-3 laboratory system. Each operating room are regulated at different negative atmospheric pressure as required in laboratory biosafety manual. The lab can be transported by air, land and sea which remove the geographical barrier particularly when it is needed in a remote setting that is not accessible by land. In terms of performance, the clinical specimen testing can be operational within 60 hours after the arrival of lab and complete suspected Ebola Virus Disease case diagnosis in less than 4 hours.

3.4 Biological Safety Level 4 Container Laboratory

Error! Reference source not found. show a BSL-4 container laboratory patent which uses the telescopic expansion mechanism with a single extension element [22]. This laboratory comes with crucial auxiliary systems installed such as ventilation system, cable and piping system, waste decontamination system. Two sections at both end of the base structure serves as utility room for engineering system installations. The center section of base structure is the laboratory room whereas the extended room serves as decontamination shower room. The designer places all the heavy laboratory equipment within the base structure to minimize unnecessary imposed load onto the moving extended compartment. Given that expansion mechanism is added within the design, it does not provide additional space for more lab functions.

Another concern regarding the design is the ventilation design inside the laboratory compartment. The position of the air vent is placed close to the BSCs which is against the general practice and guideline of research laboratory cleanroom construction. This arrangement could negatively affect the air distribution and potentially cause cross contamination across the entire lab compartment. Based on the design and system installation, the inclusion of the telescopic extension element which covers the laboratory compartment limits the possible air vent placement and make it more difficult to achieve even air distribution in a vertical airflow pattern.

ASSESSMENT SUMMARY

The summary of the reviewed models based on assessment criteria is tabulated in Table 2.

Model	Laboratory Floor Area (L x W), m^2	Biosafety Level	Mode of Transport	Expandable
MLEE-4000DC	8.00 (4 x 2)	BSL-3	Fixed-mounted Caravan	No
Certek ReadyPOD (40ft)	21.63 (2.1 x 10.3)	BSL-3	Detachable Truck Hauler	No
Mobile BSL3 Lab in Sierra Leone	21.84 (9.1 x 2.4)	BSL-3	Detachable Truck Hauler	No
BSL-4 container laboratory patent	Not available	BSL 4	Detachable Truck Hauler	Yes

Table 2 : Summary of the reviewed mobile laboratory models

Most of the mobile laboratory reviewed are design for BSL-3 and generally they are not expandable. The review found a patent describing a BSL-4 mobile laboratory build with expandable capability. However, this mobile laboratory is not available in the market.

The overall design concept of laboratory modules inclines towards the idea of standalone and self-sustaining mobile laboratory. Supplementary functions like communication system, power generation system and HVAC systems are designed to fit onto the laboratory compartment in a closely packed manner. Despite the effort to minimize space spent on these systems, engineers often cut corners on other supportive elements like workbench, furniture, changing room which are correlated to user experience. Under a space deprived setting, these adjustments may eventually affect service quality and patient satisfaction.

IV. DESIGN PROPOSITION

A virtual EMLAB as per **Error! Reference source not found.** was develop for the technical and technology feasibility study. The collapsed floor space in Figure 18, (a) is 10-meter-squares and the expanded floor space in Figure 18, (b) is approximately 30-meter-squares. The telescopic expansion provides approximate three times of floor space expansion which are more than the discussed models. This design is a revised version of mobile BSL-3 laboratory in the form of a shipping container. This design offers a multi-extension structure using telescopic expansion mechanism. It is based on the considerations that it is easier to achieve air-tight structure and the general building structure has a higher structural rigidity. Compared to the mobile BSL-4 laboratory patent which laboratory modules are fixed in position, the auxiliary system and necessary equipment of EMLAB are properly positioned and installed on the extension compartment. This allows the equipment to be moved along the expansion operation and leave additional empty space for better utilization. The facade and partition panels are customizable based on system spatial utilization and function requirement.

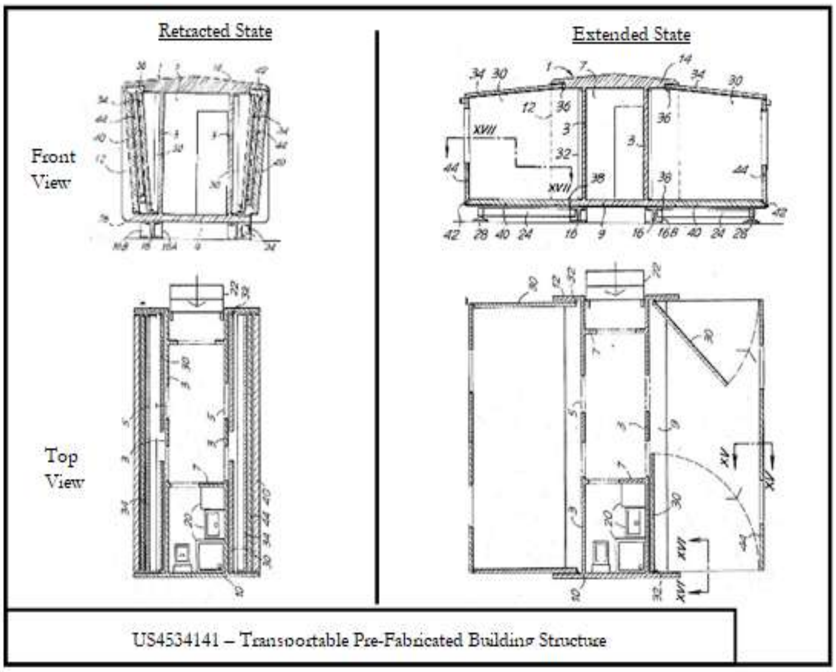

Figure 12 : Top view and front view of expandable building using hinge and linkage mechanism
Source: Patent No. US4534141 (1985)

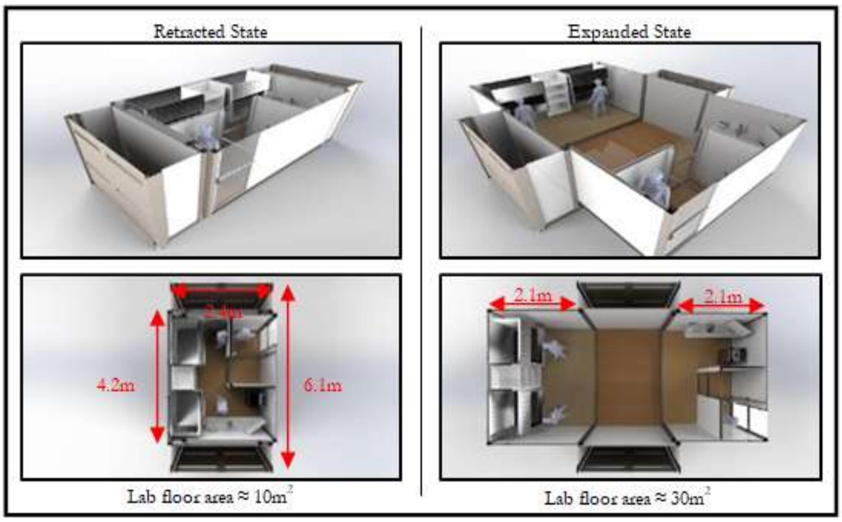

Figure 13: EMLAB Design Overview

The most important aspect of the design is the bellow-type sealing mechanism used in the design. The bellow mechanism has an elastic bellow cover with two statically sealed lips which each connects to a square bracket for installation. During the expansion process, the connections remain sealed whereas the bellow cover deforms according to the movement of the extension steel frame. This mechanism is inspired by the gangway bellow typically used in train and multi-section rail transit construction. In train construction, the gangway bellow acts as a flexible joint that flexes according to the movement between two segments of train compartment while also provide sealing purpose in bridging the gap. **Error! Reference source not found.** shows the overview of the bellow-type sealing mechanism.

The main advantage of this system is that the practicality in telescopic expansion mechanism. In this design, the sealing elements is not subjected to any load from the building system. This reduces the possibility of design failure on bellow design from structural load distribution and member deformation in relation to building structure. Since the expansion process involves an SKDOF movement only, the bellow motion can be adapted in sync with building movement via the same mechanical drive system.

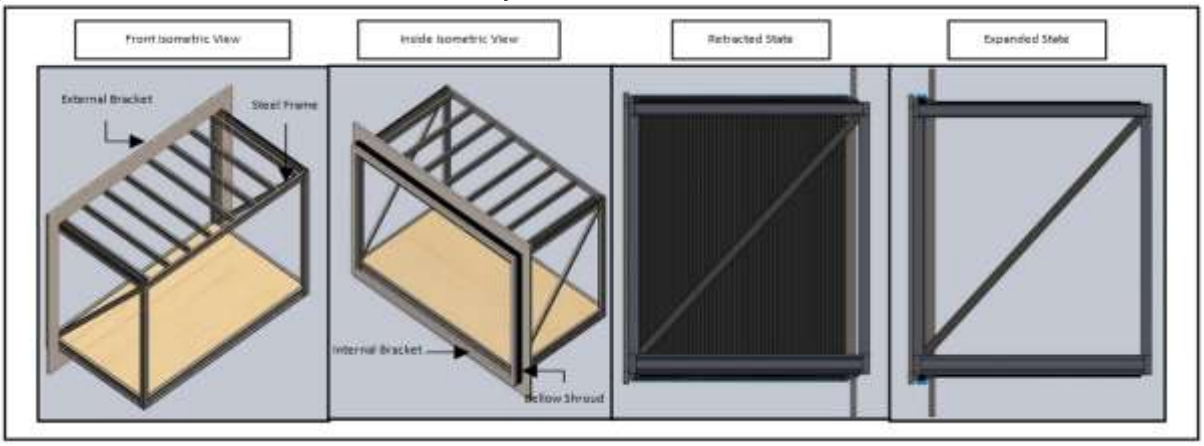

Figure 14 : Overview of expansion structure with bellow sealing mechanism

V. CONCLUSION

In this paper, EMLAB has been presented as an improved version of mobile laboratory. Origin and rationale of the concept has also been studied and discussed in detail. Mobile unit have proven to be a feasible option in making medical services more accessible for community in need. Despite it demonstrates the importance of workspace availability, the existing mobile laboratory has shown their strengths and ingenious ideas in providing optimum working environment while complies to BSL-3 and ISO cleanroom requirements. A virtue conceptual design had been developed to verify the technical and technology feasibility. The EMLAB have a 10-meter-squares floor space when collapsed and a 30-meter-squares floor space when expended. The expanded floor space can provide comfortable working space for laboratory personal to work. The proposed novel bellow sealing method can provide all time airtight sealing as part of the importance feature for achieving the BSL-3 and clean room requirement. The type of air ventilation also being selected carefully to ensure the fulfillment of the BSL-3 and clean room specification. From the studies, the EMLAB is highly feasible, practical and versatile technologically.

To fully develop EMLAB still requires further efforts and time to address technical issues such as linear motion mechanism, sealing component material, auxiliary system installation etc. This study shall serve as a foundation for future expandable mobile laboratory development.

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