Structural Design Criteria for Planetary Bases: Adaptation of Approaches used in Design of Nuclear Facilities on Earth

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Sustaining the existence of a human settlement in an extra-terrestrial environment will require the development of an infrastructure with high level of resilience. The external envelope and the structural system except forming of habitable volume should also provide a safe shelter from the extreme environment outside and the associated extreme loads: seismic activity, winds, dust storms, anthropogenic accidental loads. However, despite theoretically possible, the design of a structure to resist almost any foreseeable extreme load it is not practically possible solution. In the case of permanent planetary bases, the demand for high structural resistance should be in balance with restrains associated with the possible construction techniques and the limitations of supply of materials. Therefore it is more realistic to use graded approach specifying different level of required structural resistance for different zones of the planetary bases, eg. life support systems, shelters for the inhabitants, emergency control systems, etc.

There is a number of examples on the Earth for facilities designed for high level of resilience to abnormal natural and anthropogenic loads, as nuclear power plants, offshore oil platforms and LNG tanks probably the most appropriate to mention. The design of these facilities should balance between the requirements for high structural resistance and construction and financial restrains. Therefore graded approach is adopted specifying structural systems with different levels of safety significance and designed for different levels of external and internal loads from natural and anthropogenic origin.

The current paper provides a high level review of the main concepts, principles and approaches used for the design of hazardous facilities on Earth and in particular in the design of nuclear facilities and convert those in structural design principles and criteria for design of planetary bases.

Nomenclature

DBE	=	Design Base Event
DEC	=	Design Extended Conditions
OBE	=	Operational Base Event
PLOC	=	Probability of Loss of Crew
PLOM	=	Probability of Loss of Mission
SSC	=	Structures, systems and components

I. Introduction

SUSTAINING the existence of a human settlement in an extra-terrestrial environment will require the development of an infrastructure with high level of resilience. The external envelope and the structural system except forming of habitable volume should also provide a safe shelter from the extreme environment outside and the associated extreme loads: seismic activity, winds, dust storms, anthropogenic accidental loads. However, despite

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theoretically possible, the design of a structure to resist almost any foreseeable extreme load it is not practically possible solution. In the case of permanent planetary bases, the demand for high structural resistance should be in balance with restrains associated with the possible construction techniques and the limitations of supply of materials. Therefore it is more realistic to use graded approach specifying different level of required structural resistance for different zones of the planetary bases, eg. life support systems, shelters for the inhabitants, emergency control systems, etc. Current paper discuss the approach for safety classification of the various planetary base facilities and the use of performance oriented design approach providing different demand in terms of load intensity and design conservatism depending on the safety significance of the structure under consideration

II. Concepts for Planetary Bases

It is beyond the scope of this paper to perform an overview of the numerous concepts for permanent human settlements on other planets. Instead the reader is advised to review the work of Cohen[1,2,3] and Kennedy[4]. The NASA Habitats and Surface Construction Roadmap[1] defines three classes of lunar and planetary architecture, ranging from habitats built entirely on Earth to habitats built on the extraterrestrial surface. The three classes are as follows[1-4]:

- Class I is pre-integrated—entirely manufactured, integrated, and ready to operate when delivered to space;
- Class II is prefabricated and is space- or surface-deployed with some assembly or setup required;
- Class III is in-situ derived, with its structure manufactured using local resources available on the Moon or Mars.

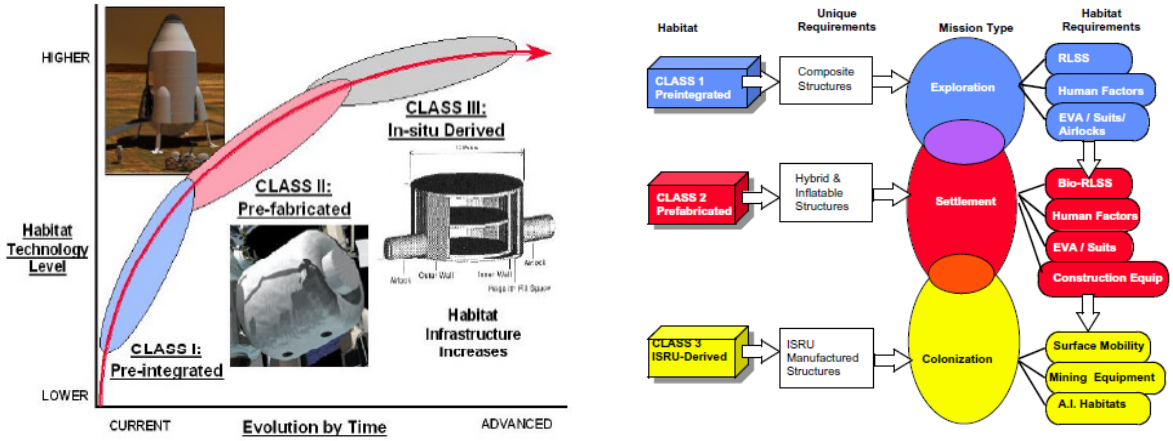

Figure 1. Habitat classification[1,2]

The current consensus is that the first permanent planetary bases will be composed mainly from Class II and Class III structures, the later becoming majority with maturing of the mission from settlement to colonisation. The most widely proposed approach is to use inflatable or rigid pressure vessels with controlled environment covered by ISRU constructed shelter to shield from radiation and extreme environment. An example of such hybrid construction is the moon base designed by Foster + Partners[5] for ESA and shown in Fig.2.

Figure 2. Lunar Habitation[5]

The presented on Figure 2 concept represents an early stage of establishment of permanent human settlement with significant dependence from Earth. A self-sufficient permanent base will require a complex set of supporting infrastructure for power generation, environmental control and food generation as core survival functions, which can be extended to research/exploration activities, mining and industrial processing of in-situ resources. An exemplarily list of facilities by type of application is given below based on the work of Benaroya[6]:

- Habitats
  - People (living and working)
  - Agriculture
  - Airlocks: ingress/egress
  - Temporary storm shelters for emergencies and radiation
  - Open volumes
- Storage Facilities / Shelters
  - Cryogenic (fuels and science)
  - Hazardous materials
  - General supplies
  - Surface equipment storage
  - Servicing and maintenance
  - Temporary protective structures
- Supporting Infrastructure
  - Foundations/Roadbeds/Launchpads
  - Communication towers and antennas
  - Waste management/ life support
  - Power generation, conditioning and distribution
  - Mobile system
  - Industrial processing facilities
  - Conduits/pipes

The mission survival in the hostile extraterrestrial environment will depend entirely on the resilience of the habitat and the supporting infrastructure facilities to the natural and technogenic hazards associated with the site and the planetary base facilities itself.

III. Brief overview of design criteria for nuclear power plants

A. Defence-in-Depth

The primary means of preventing accidents in a nuclear power plant and mitigating the consequences of accidents is the application of the concept of Defence-in-Depth (DiD)7. This concept should be applied to all safety related activities, whether organizational, behavioural or design related, and whether in full power, low power or various shutdown states. This is to ensure that all safety related activities are subject to independent layers of provisions, so that if a failure were to occur, it would compensated for or corrected by appropriate measures. Application of the concept of Defence-in-Depth throughout design and operation provides protection against anticipated operational occurrences and accidents, including those resulting from equipment failure or human induced events within the plant, and against consequences of events that originate outside the plant.

Table 1: Structure of the levels of DiD proposed by RHWG/WENRA[7]

Levels of defence in depth	Objective	Essential means	Radiological consequences	Associated plant condition categories
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation, control of main plant parameters inside defined limits	No off-site radiological impact (bounded by regulatory operating limits for discharge)	Normal operation
Level 2	Control of abnormal operation and failures	Control and limiting systems and other surveillance features		Anticipated operational occurrences
Level 3 (1) 3.a	Control of accident to limit radiological releases and prevent escalation to core melt conditions (2)	Reactor protection system, safety systems, accident procedures	No off-site radiological impact or only minor radiological impact (4)	Postulated single initiating events
Level 3 (1) 3.b		Additional safety features(3), accident procedures		Postulated multiple failure events
Level 4	Control of accidents with core melt to limit off-site releases	Complementary safety features(3) to mitigate core melt, Management of accidents with core melt (severe accidents)	Off-site radiological impact may imply limited protective measures in area and time	Postulated core melt accidents (short and long term)
Level 5	Mitigation of radiological consequences of significant releases of radioactive material	Off-site emergency response Intervention levels	Off site radiological impact necessitating protective measures(5)	-

B. Fundamental safety function:

A safety function is a specific purpose that must be accomplished for safety. In a nuclear power plant there exist the following three fundamental safety functions (from IAEA SSR-2/1):

- Control of reactivity;
- Removal of heat from the reactor and from the fuel store;
- Confinement of radioactive material, shielding against radiation, as well as limitation of accidental radioactive releases.

C. Functional isolation:

Prevention of influences from the mode of operation or failure of one circuit or system on another. Functional isolation shall refer to the isolation of inter-connected systems and subsystems from one another so as to prevent propagation of failure or spurious signals from one system to another and it also includes electrical isolation and information flow isolation.

D. Systems, structures and components important to safety (SSCs):

A general term encompassing all the plant elements (items) of a facility or activity which contribute to protection and safety, except human factors.

- Structures are the passive elements: buildings, vessels, shielding, etc..
- A system comprises several components and/or structures, assembled in such a way as to perform a specific (active) function.
- A component is a discrete element of a system.

Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves

E. Independence between systems, structures and components:

Independent systems, structures and components (SSCs) for safety functions on different DiD levels shall possess both of the following characteristics:

- the ability to perform the required safety functions is unaffected by the operation or failure of other SSCs needed on other DiD levels;
- the ability to perform the required safety functions is unaffected by the occurrence of the effects resulting from the postulated initiating event, including internal and external hazards, for which they are required to function.

Means to achieve independence between SSCs are adequate application of:

- physical separation, structural or by distance;
- functional isolation;
- diversity.

F. External hazards

Here the external hazards of concern are those natural or man-made hazards to a site and facilities that originate externally to both the site and its processes, i.e. the licensee may have very little or no control over the initiating event. Malicious actions are not included.

The assessment of natural external hazards requires knowledge of natural processes, along with plant and site layout. In contrast with almost all internal faults or hazards, external hazards may simultaneously affect the whole facility, including back up safety systems and non-safety systems alike. In addition, the potential for widespread failures and hindrances to human intervention may occur. For multi-facility sites this makes the generation of safety cases more complex and requires appropriate interface arrangements to deal with common equipment or services as well as potential domino effects.

The safety assessment for new reactors should demonstrate that threats from external hazards are either removed or minimised as far as reasonably practicable. This may be done by showing that all relevant safety Structures,

Systems and Components (SSCs) required to cope with an external hazard are designed and adequately qualified to withstand the conditions related to that external hazards.

External Hazards considered in the general design basis of the plant should not lead to a core melt accident (Objective O2 i.e. level 3 DiD). Accident sequences with core melt resulting from external hazards which would lead to early or large releases should be practically eliminated (Objective O3 i.e. level 4 DiD). For that reason, rare and severe external hazards, which may be additional to the general design basis, unless screened out (see "Screening of External Hazards" below), need to be taken into account in the overall safety analysis.

For new reactors external hazards should be considered as an integral part of the design and the level of detail and analysis provided should be proportionate to the contribution to the overall risk.

1. *Safety Demonstration*

A number of stages are envisaged:

- Identification
- Screening
- Determination of hazard parameters
- Analysis

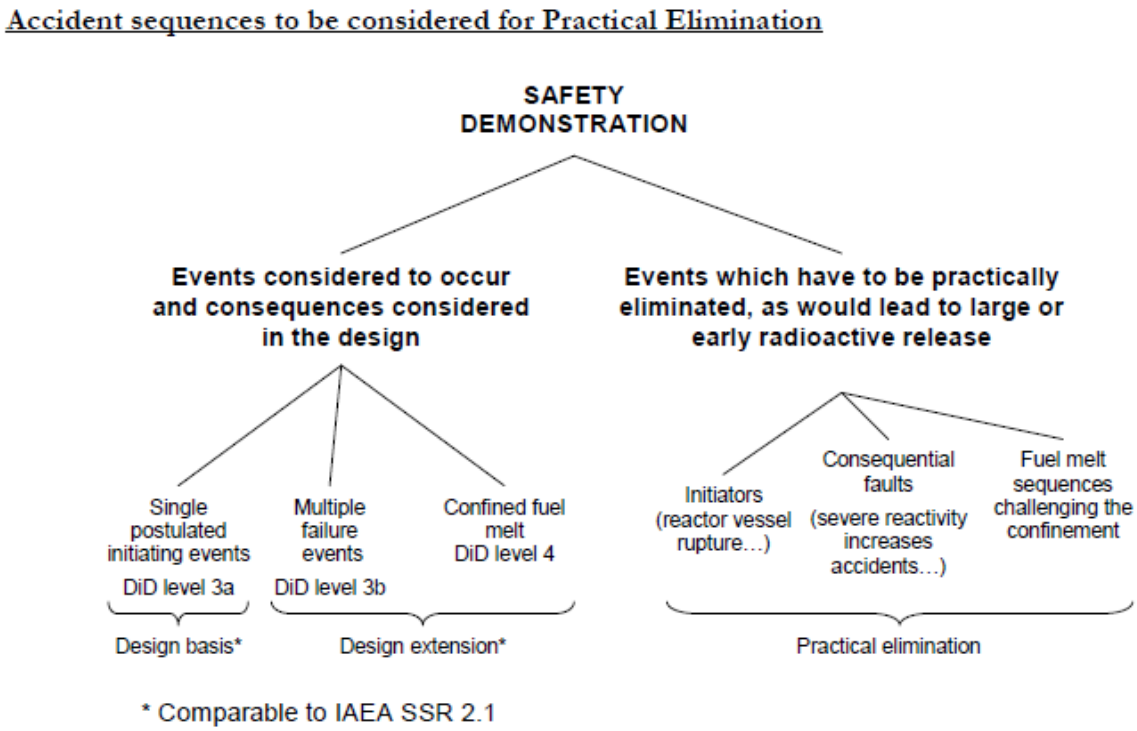

Figure 3. The concept for Safety Demonstration[7]

2. *Identification of External Hazards*

The first step in addressing the threats from external hazards is to identify those that are of relevance to the site and facility under consideration. Any identified external hazard that could affect a facility should be treated as an event that can give rise to possible initiating events.

3. *Screening of External Hazards*

Screening is used to select the External Hazards that should be analysed. The screening process should take as a starting point the complete list discussed in the previous section. Each external hazard on the list should be considered and selected for analysis if:

- It is physically capable of posing a threat to nuclear safety, and
- the frequency of occurrence of the external hazard is higher than pre-set criteria.

The pre-set frequency criteria may differ depending on the nature of the analysis that is to be undertaken. Typically for the general design basis, where the analysis will be done using traditional conservative methods, assumptions and data, the criterion will be higher than the frequency criteria used for analyses of rare and severe external hazards or PSA that could employ realistic, best estimate methods and data. Therefore the screening process may lead to separate, but compatible lists of external hazards for the range of analyses to be undertaken and there should be a clear and consistent rationale for the differences in the lists.

4. Determination of hazard parameters

All of the candidate external hazards that are selected should be characterised in terms of their severity and/or magnitude and duration. The characterisation of the external hazard will depend on the type of analysis that is to be carried out and shall be conservative for the general design basis analysis and could be realistic/best estimate for rare and severe external hazards analysis and PSA. It should be noted that for external hazards PSA, a range of frequencies and associated hazard parameters is often required. All relevant characteristics need to be specified and the rationale for their selection justified. For some external hazards:

- the ability to forecast the magnitude and timing of the event, and the speed at which the event develops may be relevant and should be considered;
- several parameters could be relevant to characterize severity and/or magnitude.

5. Analysis Considerations

The external hazards analysis includes the design of SSCs which are relevant to ensuring that the fundamental safety functions are fulfilled, development of probabilistic models where necessary, and the consideration of rare and severe external hazards. The following should be considered when undertaking this analysis:

- Minimising the risk from external hazards by initial siting of the facility
- Designing plant layout to minimise impact of external hazards (this is particularly important for multi unit facilities – also where units are of different generation)
- Justification of the lists of identified external hazards
- Justification of any hazard screening
- Combinations of external hazards that can occur simultaneously or successively within a given period of time including correlated hazards and those combinations which occur randomly
- Consideration of consequential events, such as fire or flooding following a seismic event
- External hazard induced multiple failure of safety systems and/or their support systems
- Cliff edge effects – where a small change in a parameter leads to a disproportionate increase in consequence.
- In addition to considering the impact of external hazards on the systems and components, the reliability of the buildings and structures responding to an external hazard should be taken into account.
- The PSA for external hazards should include consideration of building and structural reliability as well as system and component fragilities and should take account of the potential for human response to be affected by the external event.
- Impact of climate change and other potential time related changes that might affect the site should be considered
- Consideration should also be given to the impact of external hazards on the ability to support (emergency services) the site damaged by that external event (relevant to DiD).
- The design of the plant should reflect the external hazards analyses. Similarly the operating and maintenance procedures as well as the training etc. should take account of the external hazards analyses.
- Care must be taken where the definition of the hazard levels is imprecise, and claims are made based on the accuracy of calculations which have an accumulation of assumptions and conservatisms (or lack of)
- A clear methodology is important, along with an understanding of the associated uncertainties, both epistemic and aleatory. This is particularly important where the work also supports numerical PSA based approaches and where it is used to screen out hazards.
- The use of generic fragilities should be treated with care, as failure mechanisms may not be similar for similar types of plant, despite appearances
- Large uncertainties in characterisation of the general design basis hazards need to be addressed as part of "cliff edge" considerations
- Multiple unit sites may need additional consideration for common plant areas and mitigation

6. PRACTICAL ELIMINATION

Accident sequences that are practically eliminated have a very specific position in the Defence-in-Depth approach because provisions ensure that they are extremely unlikely to arise so that the mitigation of their consequences does not need to be included in the design. The justification of the "practical elimination" should be primarily based on design provisions where possible strengthened by operational provisions (e.g. adequately frequent inspections). All accident sequences which may lead to early or large radioactive releases must be practically eliminated.

An early release means a release that would require off-site emergency measures but with insufficient time to implement them. A large release means situations that would require protective measures for the public that could not be limited in area or time.

Accident sequences with a large or early release can be considered to have been practically eliminated:

- if it is physically impossible for the accident sequence to occur or
- if the accident sequence can be considered with a high degree of confidence to be extremely unlikely to arise (from IAEA SSR-2/1).

In each case the demonstration should show sufficient knowledge of the accident condition analysed and of the phenomena involved, substantiated by relevant evidence.

To minimize uncertainties and to increase the robustness of a plant's safety case, demonstration of practical elimination should preferably rely on the criterion of physical impossibility, rather than the second criterion (extreme unlikelihood with high confidence)

IV. Analogues with nuclear facilities on Earth

Civil nuclear industry is present on Earth from over half a century. Currently, there are well established and documented design approaches that cover all the way from siting through definition of design criteria and procedures and setting up performance driven acceptance criteria.

In order to simplify the understanding of the performance oriented design approach given in section V of this paper, some of the basic elements of a terrestrial nuclear power plant are listed in Table 1 together with their analogues meaning in case of extraterrestrial application.

Table 1: Basic elements of a terrestrial nuclear power plant (NPP) and their analogy to a planetary base

Element	**Terrestrial NPP**	**Planetary Base**
Fundamental safety functions	Control of reactivity Removal of heat from the reactor and from the fuel store Confinement of radioactive material, shielding against radiation and limitation of accidental radioactive releases	Control of habitability Confinement of the habitable artificial environment within the habitable area Shielding against radiation
Safety Classification of Structures, Systems and Components (SSC)	Define groups of SSCs depending on their importance for the overall safety and specifies different load levels and design approaches	The same as in terrestrial application
Safety Critical SSCs	Structures, systems and components needed to for the fundamental safety functions	Structures, systems and components needed for the fundamental safety functions
Containment	Contains all radioactive substances produced during normal or abnormal operation within a controlled volume in isolation with the external environment.	Contains the habitable artificial environment within the habitable area
Shielding	Reduces the radiation exposure of surroundings to acceptable limits	Reduces the radiation exposure of the habitat to acceptable limits
Shelter Structure	Structure which protect the containment and the safety critical SSCs from extreme external hazards.	Structure which protect the safety critical SSCs from extreme external hazards.

V. Design approach

It is assumed that a permanent planetary base will be composed from Class I, Class II and Class III structures with gradual increase of the percentage of Class III structures as the mission matures and transits through the phases of exploration – settlement – colonisation. It is assumed that Class I and Class II structures are designed and fabricated to high reliability level and that generally have higher level of reliability than the ISRU constructed Class III structures. The overall reliability of the planetary base as a single system will depends on the reliability of its most vulnerable elements which are assumed to be the Class III facilities. The NASA's Exploration Systems Architecture Study10 involves the risk and reliability assessment as an integral element of the architectural design process. This approach resulted in an architecture that met vehicle and mission requirements for cost and performance, while ensuring that the risks to the mission and crew were acceptable.

G. Performance levels

The performance levels of the planetary base as a system are defined based on the Figures of Merit (FOMs) for spacecraft design adopted from Cohen[10]: Crew Productivity (CP), Mission Success (Probability of Loss of Mission, PLOM) and Crew Safety (Probability of Loss of Crew, PLOC).

A single parameter that can mark the transition between the FOMs is the Habitability Index (HI) proposed by Celentano[11]. The HI is developed considering the basic habitability factors that can be determined for any given spacecraft, which are (1) environmental control, (2) nutrition and personal hygiene, (3) gravitational conditions, (4) living space and (5) crew workrest cycles and fitness programs. The Relative Value of each of these factors is calculated as ratio of the measured value divided to the optimal. The Habitability Index for the total system is determined as sum of the RVs of each major group multiplied by a weighting factor: environmental control x4, nutrition and personal hygiene x 2, gravitation x 1, living space x 2, crew work-rest cycles and fitness x 1; The sum of these weighted averaged factors is then divided to 10 (weight total) to determine the Habitability Index. The index of the Optimum Standard System is 100%.

Table 3: Relation between FOMs and the Habitability Index.

Figures of Merit (FOM)	Habitability Index
Crew Productivity	85-100%
Mission Success	>50%*
Crew Safety	>20%*

*Values are indicative for illustration purposes. Real values should be defined by appropriate studies

H. Safety classification of structures, systems and components

It could be impossible to design the Class I, Class II and Class III structures available on a planetary base for the same level of safety and this could be a potential stopper for the development of a permanent extraterrestrial human settlement. Instead designing for a constant safety level, the current paper proposes a performance oriented design approach based on safety classification of SSCs requiring different conservatism in design.

Table 4: Definition of safety classes for SSCs of planetary bases.

	Description	Example
Safety Class A	Structures, systems and components needed to prevent Loss of Crew event. These will be SSCs able to provide safe habitable shelter for the crew fur sufficient time to allow evacuation and evacuation logistics in case of Loss of Mission event	Emergency Shelter Emergency Life-Support System Emergency Power System Emergency Communication System Storage Facilities for Emergency Response Equipment Storage Facilities for Evacuation Vehicles Evacuation roadbeds/launchpads
Safety Class B	Structures, systems and components needed to prevent Loss of Mission event. These will be SSCs able to provide safe habitat for crew and all essential power, life-support and communication SSCs for sufficient time to allow mission recovery with local resources and support from Earth. SSCs not directly related to whose failure may jeopardise Safety Class B SSCs are also considered Safety Class B	Habitats (Private Suites and Essential Public Spaces) Essential Working Spaces Essential Life-Support System Essential Power System Essential Communication System Essential Industrial Processing Facilities Storage Facilities for Hazardous Materials Storage Facilities for Recovery Equipment
Safety Class C	Structures, systems and components needed to operate the planetary base at maximum capacity and to maintain optimal comfort of crew.	Habitats (Non-essential Public Spaces) Conventional Life-Support System Conventional Power System Conventional Communication Systems Conventional Industrial Processing Facilities Storage Facilities for general supplies and equipment Roadbeds and launchpads
Safety Class D	Structures, systems and components needed for extended range of operations of the planetary base	Temporary Habitats Temporary Roads Extra greenhouses Temporary Storage Facilities

I. Load levels

The use of performance based design approach will require the definition of multiple load levels to be considered in the design, starting from frequently occurring natural events or technogenic accidents and cascading up to postulated credible extreme load scenarios. The four proposed load levels are:

- Operational Base Event (OBE): natural and manmade events which in the ideal case will be derived probabilistically based on past observation data but as a minimum will be based on the maximal observed values
- Design Basis Event (DBE): extremely rare natural and manmade events which in the ideal case will be derived probabilistically based on past observation data but as a minimum will be based on the maximal credible values.
- Design Extended Condition-I (DEC-I): any foreseeable extremely rare natural and manmade events which will be based on scaling up of maximal credible values. This load level covers also any credible combination and/or sequence of DBEs
- Design Extended Condition-II (DEC-II): Postulated extreme natural and manmade events derived as scaling up of the DEC-I values. Any credible combination and/or sequence of DEC-I loads.
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J. Performance objectives

The performance objectives are defined as a matrix of requirements for the availability of any of the FOM for the different load levels and is presented in Table.5

Table 5: FOM requirements matrix for different load levels.

Figures of Merit	Operational Base Event	Design Basis Event	Design Extended Condition-I	Design Extended Condition-II
Crew Productivity	Yes	Yes	No	No
Mission Success	Yes	Yes	Yes	No
Crew Safety	Yes	Yes	Yes	Yes
Habitability Index	100%	>75%	>50%	≥20%

The assurance that the performance objectives in Table.6 will be met is provided by definition of a set of structural design criteria expressed as Factor of Safety (FoS) and required level of conservatism in the design. The proposed requirements for FOSs depending on the safety class of the SSC in consideration and the load level is given in Table 6.

Table 6: Factor of Safety requirements depending on the safety class of the structure and the considered load level.

	Factor of Safety (FOS) / Design Approach			
	Operational Base Event	Design Basis Event	Design Extended Condition-I	Design Extended Condition-II
Safety Class A	Covered by DBE	>2 / Conservative	≥1 / Conservative	≥1 / Best-Estimate
Safety Class B	>2 / Conservative	≥1 / Conservative	≥1 / Best-Estimate	None
Safety Class C	≥1 / Conservative	≥1 / Best-Estimate	None	None
Safety Class D	≥1 / Best-Estimate	None	None	None

VI. Stress-test of an Exemplarily Case Study

K. Planetary Base Description

The Hillside Base of the Mars Homestead Project[9] is selected as a case study base to apply the procedures described above in current paper. The Hillside Base[9] shown on Fig.4 is designed as partially underground, partially exposed facility built largely from local materials. Using a combination of imported and local resources, the Hillside Base will be approximately 90% self-sufficient by mass and will provide the settlers with the industrial capabilities they need to explore and settle the frontier. The Candor Chasma at reference coordinates 69.95W x 6.36S x -4.4km is selected as likely site for the Hillside Base. This site is part of the Valles Marineris canyon complex and has been photographed extensively by the Mars Global Surveyor. It consists of a number of mesas suitable for providing shelter as well as room for expansion.

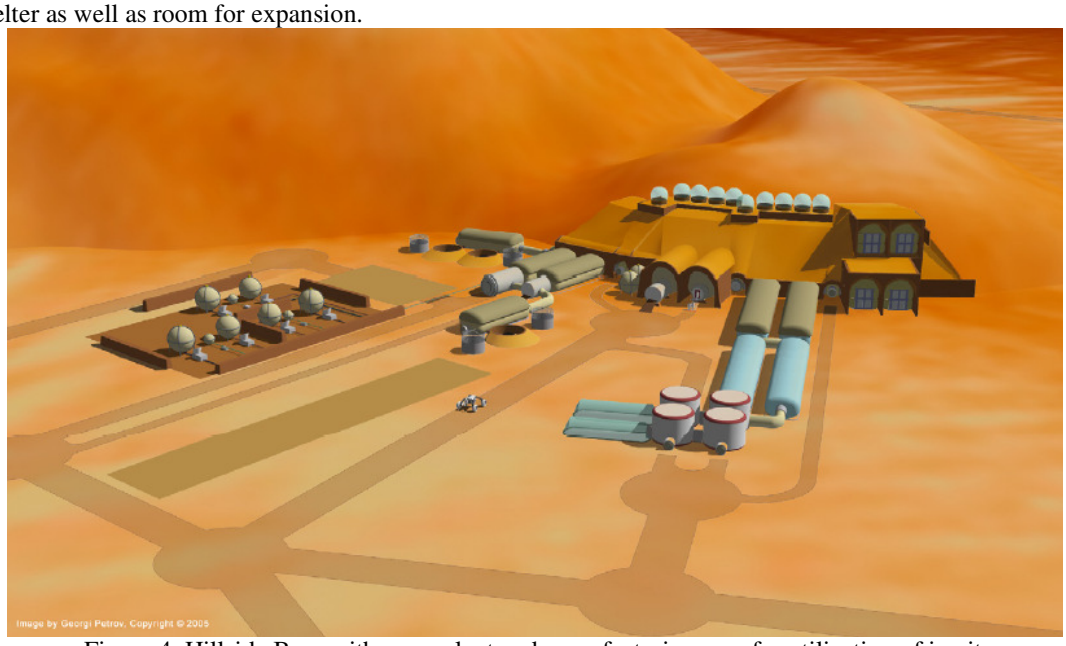

Figure 4. Hillside Base with a gas plant and manufacturing area for utilization of in-situ resources[9]

The Hillside Base reference design provides habitation for 12 people and covers 800 square meters, with greenhouses, fuel, nuclear plants, and manufacturing facilities located outside. Private living spaces, labs, and common areas are situated inside the mesa, with some of the rooms providing views of the outside. Topographical view is shown on Fig.5. Section cut is shown on Fig.6.

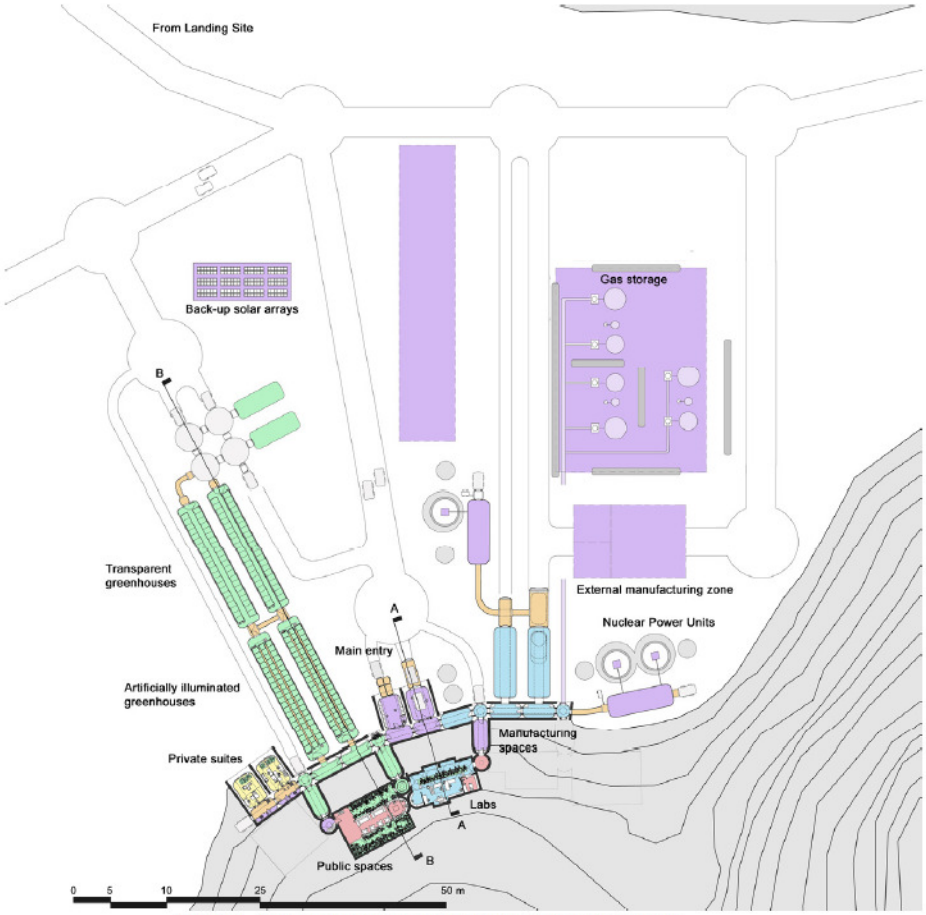

Figure 7. Hillside Base reference design--topographical view.

Figure 5. Hillside Base reference design – topographical view[9]

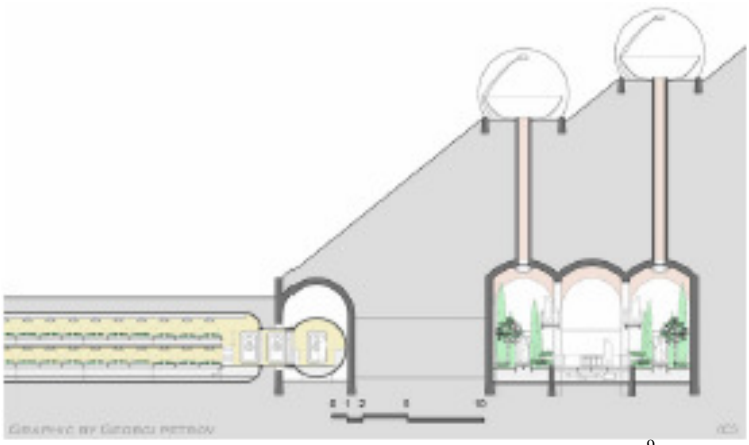

Figure 6. Hillside Base reference design – section cut[9]

7. *Entrance*

The main entrance is composed of two pressurized modules: the main entry and a garage. The main entry module consists of two airlocks with multiple egress options. One of the airlocks will provide direct access to the Martian surface for daily exterior activities, such as construction and repair work. The other airlock will be a docking port for rovers

8. Social Spaces

The settlement will include areas for the entire group to gather in one place. These spaces are arranged along the infrastructure, with vegetation mediating the spaces between humans. The human activities are located in the center with the trees surrounding them on two sides. This is where the community comes together on a daily basis. The space includes the communal kitchen and dining areas. The two bays above the dining area are covered with two-story high barrel vaults marking this as a special subspace of the segment. The second level includes balconies, catwalks, public work spaces, and also spaces for exercise and entertainment.

9. The Greenhouse

The greenhouses are the largest modules of the settlement and are situated on the flat land extending away from the mesa. The greenhouses are built with redundancy in mind: if one unit fails demand can be covered by adjacent units. Each module has complete capability of cycling water, air, and nutrients. The waste handling and water purification units are in the greenhouses and their adjacent modules. Note that 100% recycling in not required, since gases, water, and minerals can be extracted from Mars air and soil. Two greenhouses are transparent, to take advantage of natural sunlight, supplemented with artificial light as needed. The other two greenhouses are opaque, covered with regolith, and artificially lit.

10. Pressurized Construction

The reference design of the HillsideBase utilises different construction techniques to handle the internal air pressure. Rigid cylinders are used in the flat, open areas away from the hillside. The smaller, standard size rigid modules would be wound fiberglass, constructed inside an inflatable construction tent. The larger ones must be sheet metal welded on-site. Most would be covered with at least 1 meter of regolith to provide minimal radiation protection. These modules are: the private suites, greenhouses, greenhouse support spaces, nuclear power 'balance of plant' in purple, the airlock support spaces, and some manufacturing spaces. Buried Masonry vaults and domes are used for much of the living space. To hold the internal pressure, between six and ten meters of regolith (depending on composition and level of compacting) must be placed over them. Obviously, the masonry must be strong enough to hold the weight of the overburdened, and have buttresses shaped to hold the weight whether they are pressurized or depressurized. To keep the air from leaking, the bricks are glazed and caulked on the inside. In addition, alternating layers of sand and vapor barrier are placed outside the masonry to collect air which does leak, and suck it back into the air processing equipment to be recovered. These modules are at the bottom of Figure 5 shown with thick walls, and at the right on figure 6. They include the: two-story public space, labs, kitchen, dining area. Masonry over Inflatables are used at the edge of the hillside, to transition from the deeply buried masonry vaults to the open area. These are simple inflatable cylinders made from thinner fiberglass or cloth or thin sheet metal. They are used inside masonry vaults to protect them. The masonry also holds the hillside back and provides radiation protection. These modules are at the middle of Figure 5 shown as thick walls with rounded lines inside them, also at the middle of figure 6. They include the: private suites, waste treatment, greenhouse support, main entry, suit room, rover garage, and some manufacturing spaces

L. Hazard Identification

Exemplarily hazard identification relevant to the Hill Base is shown in Table 7.

Table 7: Hazard identification matrix

Hazard	**Origin**	**Description**	**Source**	**Effect on Fundamental Safety Functions**
Radiation	Natural	Solar radiation	Ambient	Effects on habitability
	Anthropogenic	Radiation from technogenic activities	Nuclear reactors, nuclear spent fuel, nuclear waste	Effects on habitability
Extreme Temperatures	Natural	Maximal and minimal temperatures	Ambient	Effects on habitability Thermal loads for life-support systems(heating and cooling) Thermal loads on structures (stresses/strains)
	Anthropogenic	Max/min temperatures from various mechanical	Mechanical equipment of Life-support	Thermal loads on structures (stresses/strains)

		equipment	systems and industrial facilities	
Dust Storm	Natural	Abrasive dust blown by the winds	Ambient	Effects on life-support systems
Meteoroid Impact	Natural	High speed impacts on solid objects of different size	Space	Damages on structures, systems and components Induced seismicity
Seismicity	Natural	Ground shaking	Maritain crust	Damages on structures, systems and components Seismic induced technogenic hazards – fire, explosion, loss of air tightness, leakage of essential fluids
Induced Seismicity	Natural	Ground shaking induced by meteoroid impacts	Space	Damages on structures, systems and components Seismic induced technogenic hazards
	Anthropogenic	Underground explosion of mechanical equipment	Nuclear reactors Pressure vessels	Damages on structures, systems and components Seismic induced technogenic hazards – fire, explosion, loss of air tightness, leakage of essential fluids
Over-pressurisation	Anthropogenic	Elevated pressure on internal surfaces of hermetic volumes	Malfunction of essential equipment	Damages on structures Loss of air tightness
Explosion	Anthropogenic	Blast wave and debris	Malfunction of pressurised equipment	Damages on structures, systems and components Induced technogenic hazards
Fire	Anthropogenic	Elevated temperature	Malfunction of equipment/vessels containing flammables	Damages on structures, systems and components Induced technogenic hazards
Mechanical impact	Anthropogenic	Flying debris of mechanical equipment	Malfunction of rotating equipment;	Damages on structures, systems and components Induced technogenic
Vehicle impact	Anthropogenic	Accidental crash of a crew or cargo vehicle during landing or taking off	Malfunction due to landing or launching operations	Damages on structures, systems and components Induced technogenic hazards – fire, explosion, loss of air tightness, leakage of essential fluids

M. Safety Classification of the Facilities

The safety classification of the facilities comprising the Hill Base is shown in Table 8.

Table 8: Safety classification matrix

Facility name	Safety Class	Safety Assessment
Public spaces	Safety Class A	Based on the original purpose[9] this facility should be rated as Class C, but in this study it is considered Class A as it will serve as emergency shelter
Labs	Safety Class A	Based on the original purpose[9] this facility should be rated as Class B, but in this study it is considered Class A as it will serve as emergency life support and power source
Main entry	Safety Class A	Based on the original purpose[9] this facility should be rated as Class C,

		but in this study it is considered Class A as it will serve as emergency exit and storage for evacuation vehicles
Manufacturing spaces	Safety Class B	Rated as Class B as it is assumed that will serve as an essential working space to support recovery operations
Nuclear Power Units	Safety Class B	Rated as Class B as nuclear accident will lead to abandoning of the base – LOM. However, this is discussable as major nuclear accident may lead directly to Loss of Crew
Private suits	Safety Class C	Can be reconstructed after a major accident. Crew will occupy the public spaces and/or the pressurised exploration vehicles
External Manufacturing Zone	Safety Class C	Can be reconstructed after a major accident.
Artificially illuminated greenhouses	Safety Class C	Can be reconstructed after a major accident.
Gas Storage	Safety Class C	Can be reconstructed after a major accident.
Back-up solar arrays	Safety Class C	Can be reconstructed after a major accident.
Landing site	Safety Class C	Can be reconstructed after a major accident.
Road to the Landing Site	Safety Class C	Can be reconstructed after a major accident.
Other roads on the site	Safety Class D	Can be reconstructed after a major accident.
Transparent greenhouses	Safety Class D	Can be reconstructed after a major accident.

N. Safety Assessment

Comprehensive safety assessment of the Hill Base should include a safety matrix where each element of the base is checked for each external and internal hazard and their credible combinations. This is to be completed for each load level – OBE, DBE, DEC – I and DEC-II. The overall safety of the Hill Base than will be assessed as a single system and the risk for LOM and LOC will be function of the reliability of each element and the redundancy of the system. However, such detailed assessment needs detailed input data for the likely severity of each load level for each hazard, as well detailed structural/mechanical properties of all SSC.

For demonstration purposes, in this study the safety of each element of the Hill Base is verified by generic safety assessment based on engineering judgement and focusing only on identification of the vulnerable elements of each facility. The safety assessment matrix is shown in Table 9

Table 9: Safety assessment matrix

Facility name	**Safety Assessment**
Public spaces (Safety Class A)	This is a masonry vault structure buried in the hill and therefore should have high level of resilience for most of the identified hazards for all load levels from OBE to DEC-II. The main vulnerability comes from the sunlight pipes which connect the vaults with the sunlight collecting domes above, which reduces the reliability of the Public Spaces element in case internal overpressure, slope failure of the hill (due to induced seismicity for example), etc.
Labs (Safety Class A)	This is a masonry vault structure buried in the hill and therefore should have high level of resilience for most of the identified hazards for all load levels from OBE to DEC-II. The main hazard will be internal man made hazards - fire, toxic gases, flooding and mechanical impacts in case of malfunction of the equipment/vessels inside
Main entry (Safety Class A)	This is an exposed structure which can be subjected to all identified hazards. The Main Entry will not be able to resist external hazards from level DEC-I and DEC-II which may lead to Loss of Mission and Loss of Crew if the Main Entry if is not well isolated from the internal premises and there is no other means for evacuation transport
Manufacturing spaces (Safety Class B)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DEC-I and DEC-II. This facility should be well isolated from the internal premises.
Nuclear Power Units	Buried structures that should be able to resist most of the identified hazards for all load

(Safety Class B)	levels from OBE to DEC-II as long as it is well isolated from the balance of plant which is exposed structure.
Private suits (Safety Class C)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DEC-I and DEC-II. This facility should be well isolated from the essential internal premises.
External Manufacturing Zone (Safety Class C)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DEC-I and DEC-II. This facility should be well isolated from the essential internal premises
Artificially illuminated greenhouses (Safety Class C)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DEC-I and DEC-II. This facility should be well isolated from the essential internal premises
Gas Storage (Safety Class C)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DEC-I and DEC-II. This facility should be well isolated from the essential internal premises
Landing site (Safety Class C)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DEC-I and DEC-II.
Road to the Landing Site (Safety Class C)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DBE, DEC-I and DEC-II.
Back-up solar arrays (Safety Class D)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DBE, DEC-I and DEC-II.
Other roads on the site (Safety Class D)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DBE, DEC-I and DEC-II.
Transparent greenhouses (Safety Class D)	This is an exposed structure which can be subjected to all identified hazards. This element will not be able to resist external hazards from level DBE, DEC-I and DEC-II.

O. Potential Safety Improvements

Summary of the potential safety improvements is presented in Table 10.

Table 10: Safety improvement matrix

Facility name	Safety Improvements
Public spaces (Safety Class A)	Installation of mechanical hatches on the interface with all neighbouring facilities. Installation of mechanical isolation valves on the interface with all sunlight pipes Integrating of an additional space as an emergency shelter within the facility to serve as temporary living space for all crew after a major external event and loss of the private living space
Labs (Safety Class A)	Installation of mechanical hatches on the interface with all neighbouring facilities Integrating in to the design of protective measures for fire, flooding, toxic gases, etc.
Main entry (Safety Class A)	This element should be also buried deeply in the hill and isolated from the external space by reliable solid mechanical hatch or to include in the design separate emergency entry/exit with higher reliability. The design should include also sufficient space for emergency/evacuation vehicles.
Manufacturing spaces (Safety Class B)	Installation of mechanical hatches on the interface with all neighbouring facilities.
Nuclear Power Units (Safety Class B)	No need for safety improvements
Private suits (Safety Class C)	No need for safety improvements.
External Manufacturing Zone (Safety Class C)	No need for safety improvements

Artificially illuminated greenhouses (Safety Class C)	No need for safety improvements
Gas Storage (Safety Class C)	No need for safety improvements
Landing site (Safety Class C)	Additional landing side to improve redundancy by geographical separation
Road to the Landing Site (Safety Class C)	Additional road to improve redundancy by geographical separation.
Back-up solar arrays (Safety Class D)	No need for safety improvements
Other roads on the site (Safety Class D)	No need for safety improvements.
Transparent greenhouses (Safety Class D)	No need for safety improvements.

VII. Conclusion

The current paper provides a high level review of the main concepts, principles and approaches used for the design of hazardous facilities on Earth and in particular in the design of nuclear facilities and convert those in structural design principles and criteria for design of planetary bases. The proposed approaches for hazard identification and safety assessment are applied as kind of "stress test" of a concept for permanent settlement on Mars available in the literature.

Significant additional research work is still needed on order to develop a systematic approach for siting and design of permanent extra-terrestrial human settlements

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