DESIGN FOR MINIMUM RISK IN REMOTE MAINTENANCE SYSTEM DEVELOPMENT FOR FUSION POWER PLANT

TRUONG, VAN DUNG
Abstract

The thesis develops a new design methodology for minimum risks at the early design phase by establishing a risk-based function structure and physical-effect abstraction of risk parameters for analysis and simulation. The methodology is implemented through a study case of the hexapod robot, a part of a remote maintenance system working inside the In-BioShield area of the DEMOnstration Fusion Power Plant. Several solutions were chosen during the preliminary analysis of this study case, including using thermal and magnetic shields with special materials, adding clearances to mitigate risks related to thermal expansion and using a shock absorber with unique fasteners for minimising vibration resonance impacts. A simulation model was constructed to evaluate the performance of these design solutions. The results confirm that risks are minimised satisfactorily with the new design approach. The study helps recommend a new design methodology for identifying and minimising risks in the early design stages.

Keywords  Remote maintenance system, risk in early design, DEMO, In-Bioshield, design development, fusion power plant, product design and development, minimum risk, risk function structure
## Contents

PREFACE .................................................................................................................. 6

SYMBOLS AND ABBREVIATIONS ......................................................................... 7

1 INTRODUCTION .................................................................................................... 11
  1.1 Background ...................................................................................................... 11
  1.2 Motivation ....................................................................................................... 12
  1.3 Research Objective ......................................................................................... 13
  1.4 Research Methodology and Approach ......................................................... 13
  1.5 Research Scope ............................................................................................. 14
  1.6 Research Contribution .................................................................................. 14
  1.7 Thesis Structure ............................................................................................ 14

2 RESEARCH CLARIFICATION ............................................................................. 16
  2.1 Literature Review and Product Benchmarking ............................................. 16
    2.1.1 In-Bioshield Component Description .................................................. 16
    2.1.2 DEMO Maintenance Overview ............................................................. 18
      2.1.2.1 Maintenance Scenarios ............................................................... 18
      2.1.2.2 Review of Potential In-Bioshield RM Systems .......................... 19
  2.2 Identifying Requirements for Risk Minimisation ........................................ 23
    2.2.1 Inbioshield Design Requirements ....................................................... 23
    2.2.2 Design Drivers ..................................................................................... 23
    2.2.3 Risk Minimisation Requirements ....................................................... 25

3 DESIGNING FOR MINIMUM RISK METHODOLOGY .................................... 27
  3.1 State of The Art ................................................................................................ 27
    3.1.1 Function Structure Diagram .................................................................. 27
    3.1.2 Risk Minimisation in Design ............................................................... 28
  3.2 Background to Risk Analysis .......................................................................... 29
    3.2.1 High Temperature - Heat ...................................................................... 29
      3.2.1.1 Heat Transfer by Conduction ...................................................... 30
      3.2.1.2 Heat Transfer by Convection ...................................................... 31
      3.2.1.3 Heat Transfer by Radiation ......................................................... 31
      3.2.1.4 Rate of Heat Transfer ................................................................. 31
      3.2.1.5 Design Consideration for Thermal Risk Mitigation .................... 33
    3.2.2 Thermal Expansion ............................................................................... 34
3.2.3 Creep ................................................................. 35
3.2.4 Stress Relaxation .................................................. 37
3.2.5 Nuclear Radiation ................................................ 38
  3.2.5.1 Nuclear Radiation Shielding .................................. 39
  3.2.5.2 Nuclear Radiation Hardening .................................. 40
3.2.6 Magnetic Field ..................................................... 41
3.2.7 Vibrations .......................................................... 44
3.2.8 Pressurised Water .................................................. 47
3.3 Function Risk Minimisation Model ............................... 48
  3.3.1 Risk-Minimisation-Based Overall Function ..................... 48
  3.3.2 Risk-Minimisation-Based Function Structure Modelling ...... 50
  3.3.3 Risk Minimisation Function Structure and Physical Relationship ................................................................. 54
4 DESIGNING FOR MINIMUM RISK ........................................ 56
  4.1 Hexapod Study Case .................................................. 56
  4.2 Minimum Risk Design Solution ..................................... 58
    4.2.1 Concept Generation ............................................... 59
      4.2.1.1 Concept A .................................................... 59
      4.2.1.2 Concept B .................................................... 60
      4.2.1.3 Concept C .................................................... 60
      4.2.1.4 Concept D .................................................... 61
      4.2.1.5 Concept E .................................................... 62
      4.2.1.6 Concept F .................................................... 62
    4.2.2 Selected Concept for Further Analysis ......................... 63
  4.3 Preliminary Analysis to Minimise Risk ............................ 63
    4.3.1 Structure Consideration ........................................ 64
    4.3.2 Material Consideration ........................................ 65
    4.3.3 Fastener Consideration ....................................... 66
    4.3.4 Magnetic Field Solution ........................................ 67
    4.3.5 Vibration Solution ............................................. 68
    4.3.6 Thermal Transfer Solution ..................................... 69
    4.3.7 Thermal Expansion Solution ................................... 70
    4.3.8 Creep and Relaxation Solution ................................ 72
    4.3.9 Dynamic Loads Solution - Design for Self-help ............. 74
4.4 3D Model of the Concept Solution ........................................... 76
5 SIMULATION FOR MINIMUM RISK ............................................. 78
  5.1 Heat ......................................................................................... 80
  5.2 Vibrations ................................................................................ 81
  5.3 Creep and Relaxation ............................................................... 82
6 DISCUSSION .................................................................................. 83
7 CONCLUSIONS .............................................................................. 84
8 REFERENCES .................................................................................... 86
9 APPENDIX A: 2D DRAWINGS ......................................................... 89
10 APPENDIX B: CREEP DATA ............................................................ 92
11 APPENDIX C: SIMULATION CODES .............................................. 93
  11.1 Thermal Insulation ................................................................. 93
  11.2 Vibration Isolator ................................................................. 94
  11.3 Risk Minimisation Evaluation ............................................... 95
    11.3.1 Simulink Diagrams ............................................................ 95
    11.3.2 Visualisation Codes .......................................................... 98
PREFACE

The thesis was completed during the work at VTT Technical Research Centre of Finland and financially supported by the EURO Fusion program during the funding period 9 (2020-2027).

In the summer and autumn of 2022, many self-research efforts are spent to complete this work. It is hard to complete this thesis alone without any guidance and helps from my mentors. First, I want to thank Dr William Brace and Dr Antti Pulkkinen for believing in and guiding me during my work at VTT. Secondly, I want to express my appreciation to Professor Kalevi Ekman, my supervisor, for teaching me valuable knowledge about product development. The time studying at the Aalto Design Factory was one of my fondest memories, where I developed myself and became more mature in this study and career path. I would also like to thank my colleagues Siren Mika, Mikko Siuko and the rest of the Agile Intelligent Production Systems team (BA5605) for your support and the time I worked here.

Finally, I want to dedicate this thesis to my father - Van Thin Truong, who has sacrificed and spent his entire life working offshore, encouraging me in my higher study, and raising my family and me to this day. I wish all the bests to you.

Espoo, November 2022
Truong, Van Dung
SYMBOLS AND ABBREVIATIONS
Symbols

\( A \) The surface area where the heat transfer occurs
\( A_s \) Tensile stress area of a bolt
\( A_0 \) Oscillation magnitude
\( B \) Flux density
\( B_u \) Build-up factor
\( c \) Damping coefficient
\( C_i \) Component inspected
\( C_R \) Component repaired
\( C_{RL} \) Component replaced
\( C_p \) The specific heat capacity of the substance
\( C_1, C_2 \) The material constant depends on the materials \( (C_1 > 0) \)
\( C_3 \) Material constant defining the creep temperature dependency
\( d \) Diameter
\( D \) Absorbed dose rate before shielding
\( D_0 \) Absorbed dose rate after shielding
\( D_s \) Physical dimension depicting the shield’s size
\( E \) Young’s modulus of material
\( E_{in} \) Energy transferred from the outside into the system
\( E_{out} \) Energy transferred from the system to outside
\( E_{aux} \) Auxiliary energy
\( \dot{\varepsilon}_c \) Creep rate
\( E_{def} \) Energy deformation
\( E_{hu} \) Human energy
\( F_D \) Dynamic forces
\( F_{damping} \) Damping force
\( F_{external} \) External force
\( F_{t,Rd} \) Design tension resistance per bolt
\( f_{ub} \) Ultimate tensile strength
\( g \) Gravitational acceleration
\( h \) Depth
\( H_0 \) Magnetic field strength to be shielded
\( H(r) \) The magnetic field of the reference point with shielding
\( h_1 \) Enthalpy of the airflow in
\( h_2 \) Enthalpy of the airflow out
\( H^{inc}(r) \) The magnetic field of the reference point without shielding
\( k \) Thermal conductivity of the material
\( l \) The original length of material
\( m \) Weight of the object
\( m \) The mass flow rate of the exchange air
\( m_{displaced \ fluid} \) Weight of the fluid being displaced by the object
\( m_{object \ in \ fluid} \) Weight of object in fluid
**$m_{\text{object in vacuum}}$**  Weight of object in vacuum

**$M$**  Material

**$M_{\text{def}}$**  Material deformation

**$P$**  Total power capacity of the electrical system

**$p_0$**  The pressure of zero reference point of the pressure

**$P_W$**  Pressurised water

**$Q_{\text{cond}}$**  Rate of heat conduction

**$Q_{\text{conv}}$**  Rate of heat convection

**$Q_{\text{rad}}$**  Rate of heat radiation

**$Q_2$**  The auxiliary heat energy from the system

**$Q_e$**  The excessive energy generated by the system

**$r$**  Frequency ratio

**$R_M$**  Minimised Risk

**$S$**  Input signal

**$S_{\text{real}}$**  Output signal

**$t$**  Material thickness

**$T$**  Target temperature

**$T_0$**  Initial temperature

**$T_a$**  In-BioShield temperature

**$T_f$**  The surface temperature of fluid/ gases

**$T_{\text{homo}}$**  Homogenous temperature

**$T_S$**  The surface temperature of solid

**$T_{S_r}$**  The absolute temperature of the emitting surface

**$T_{\text{surr}}$**  The absolute temperature of the surrounding environment

**$v$**  Velocity

**$v_0$**  The velocity of the system in initial conditions

**$X$**  displacement magnitude of the system

**$x_{\text{max}}$**  Maximum displacement

**$Y$**  displacement magnitude of the seismic event

**$\Sigma_R$**  Mass attenuation coefficient

**$\rho$**  Temperature difference

**$\xi$**  Average thermal expansion coefficient between $T$ and $T_0$

**$\gamma_{M2}$**  Partial safety factor for resistance of bolts

**$\varepsilon$**  The emissivity of the surface

**$\varepsilon_T$**  Total strain caused by stress relaxation

**$\varepsilon_{\text{thermal}}$**  Thermal strain

**$\varepsilon_e$**  The strain of spring in the Maxwell model

**$\varepsilon_p$**  The strain of a dashpot in the Maxwell model

**$\eta_e$**  Power coefficient of the electrical system

**$\sigma_{\text{thermal}}$**  Thermal stress

**$\sigma_0$**  Preload stress

**$\omega_n$**  Natural angular frequency of the system
\( \phi_B \) Bending shape factor

\( \Delta E_{\text{system}} \) The net energy transfer by heat, work, and mass

\( \Delta L \) Length changes caused by thermal expansion

\( \alpha \) Linear thermal expansion coefficient

\( \eta \) Viscosity

\( \mu \) Permeability of a material

\( \xi \) Damping ratio

\( \rho \) Density of material

\( \sigma \) Current stress

\( \omega \) Angular frequency

**Operators**

\( \frac{d}{dt} \) Derivative with respect to variable \( t \)

\( A \cdot B \) Dot product of \( A \) and \( B \)

**Abbreviations**

BOM Bill of Materials
CAD Computer-Aided Design
CF Component-Failure Matrix
COTS Commercial off-the-shelf
DD Design Driver
DEMO Demonstration Fusion Power Plant
DRM Design Research Methodology
DS-I Descriptive Study I
DS-II Descriptive Study II
EC Function-Component Matrix
EF Function-Failure Matrix
FEA Finite Element Analysis
FFDM Function-Failure Design Method
FMEA Failure Mode and Effect Analysis
FPP Fusion Power Plants
FSD Function Structure Diagram
ITER International Thermonuclear Experimental Reactor
JET Joint European Torus
MA Machine Availability
MTBF Mean Time Between Failures
MTTR Mean Time To Repair
PS Prescriptive Study
RC Research Clarification
RED Risk in Early Design
RFSD Risk minimisation-based Function Structure
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM</td>
<td>Remote Maintenance</td>
</tr>
<tr>
<td>RMR</td>
<td>Risk Minimisation Requirements</td>
</tr>
<tr>
<td>SIC</td>
<td>Safety Importance Classification</td>
</tr>
<tr>
<td>TR</td>
<td>Transmission Ratio</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

1.1 Background

Over the last fifty years, the fusion power plant has gained increasing attention due to its promising efficiency, reliability, and safety compared with conventional fission nuclear power plants. Fusion power plants (FPP) typically replicate the reactions observed inside the sun, called the fusion reaction. This reaction combines two light nuclei into a single heavier nucleus by using two isotopes of hydrogen, which are Tritium and Deuterium, expressed by

\[
\frac{2}{1}D + \frac{3}{1}T \rightarrow \frac{4}{2}He (3.5\text{MeV}) + \frac{1}{0}n (14.1\text{MeV})
\] (1)

The fusion reaction releases enormous energy under the plasma form and has been utilised to rotate turbines and produce electricity. All these processes are taken place inside a tokamak building, as shown in Figure 1.

![Figure 1 The working principle of a fusion power plant [1]](image)

Since the FPP operates based on the fusion reaction and the plasma is controlled by intense magnetic fields, humans become inappropriate to work directly inside this harsh environment area. However, this problem is overcome by using autonomous robots and Remote Maintenance (RM) equipment.

There have been several nuclear fusion development projects with RM research recently. One is the Joint European Torus project (JET), the first fusion reactor for research and a symbol of an initial step in making the fusion power plant. It was the first device to build, produce, and control fusion power (up to 16.1MW in 1997 [2]). Later, the International Thermonuclear Experimental Reactor (ITER) project inherited basic designs from JET with
further improvements to deliver integrated physics and engineering on the scale of 500MW power.

However, JET and ITER are restricted to laboratories and are not yet commercially proven. The DEMonstration Power Plant (DEMO) project started as a single step between ITER to solve this need. It aims to improve the gross thermal output of the fusion power plant from 500MW to 2000MW and validate thermonuclear fusion as an economically viable means of generating power. The initial timeline is demonstrated in Figure 2. The design duration is estimated to last until 2030, collaborating with multiple research institutes inside and outside Finland and across Europe.

The success of the DEMO project depends on many factors, including the success of RM activities using robots and autonomous systems. However, many engineering risks, including high temperature, radiation, magnetic fields, pressurised water, and cleanliness, still exist, potentially impacting autonomous equipment and challenging development efforts during the design of the systems.

1.2 Motivation

Risks in engineering and design are failure modes with corresponding likelihood and consequences under situational scenarios. They are commonly forecasted by several standard techniques like the Failure Mode and Effects Analysis (FMEA) [3], Function-Failure Design Method (FFDM) [4] or Risk in Early Design (RED) [5]. These tools allow designers to address risks and analyse them based on previous experiences or historical failure data. The FMEA approach is good at indicating physical causes, risk frequencies and mitigation actions but is ineffective during the functional design at the early design phase. The FFDM method has solved this weakness by associating them with product functions under matrix formulations. FFDM’s outcomes can be mapped with likelihood and consequences by the RED method and represented under a risk fever chart. However, these methods mainly address hazards; little effort has been focused on identifying a methodology that mitigates them in the early phases, right after requirements are revealed. Therefore, a new methodology to reduce risks during conceptual design is required to overcome this challenge.
1.3 Research Objective

The goal of this thesis is to develop a new design methodology, Risk-minimisation-based Function Structure (RFSD), as a part of the conceptual design phase to minimise risks in the early design stages. The methodology is implemented on the on a sub-system of the hexapod robot as a design case study and evaluated through simulation. The research is an important part of designing a component of an RM system with minimum risk for working inside the In-BioShield area of the DEMOnstration Fusion Power Plant.

1.4 Research Methodology and Approach

In order to achieve the research objective, the thesis applies a systematic method that uses the Design Research Methodology (DRM) proposed by Blessing et al. [6] as an approach and guidelines to improve design research quality. Figure 3 demonstrates the research methodology used in this work.

Figure 3 Research Methodology follows the DRM framework

In the RC stage, there was a clarification of the research problem. This includes the study of descriptive and prescriptive literature, contextualising the fusion power plant medium in which the designed system is applied, and product benchmarking. Based on the findings, design requirements were identified, and the risk minimisation requirements were formulated to be implemented in the minimum risk model.
Having a clear goal and focus from the RC stage, there was a further literature review in DS-I to identify crucial influencing factors, elaborate on the initial findings, and develop the design methodology for minimum risk. In the PS stage, the design methodology for minimum risk is implemented in a case study. The case study method offers a systematic approach to examining occurrences, gathering data, analysing information, and reporting outcomes.

In the Descriptive Study-II stage, the risk minimisation performance is evaluated through computer simulation using Matlab Simulink.

1.5 Research Scope

The thesis is performed within the engineering design process. The engineering design covers the product's design through systematic and progressive steps: identifying problem spaces, establishing concepts, embodiment design and detailed design. The thesis focuses on the early design phase, comprising the identifying problem spaces and establishing concepts.

The scope of the thesis is under the context of developing RM systems for the DEMO FPP, considering potential risks. Mitigation of risks is an important aspect of system design in FPP. Risks in this work are restricted to the effects of heat, radiation, magnetic field and vibrations on the RM system operating in the In-BioShield environment of the DEMO FPP. The research concentrates on minimising these risks' effects in the early design phase and does not consider risk mitigation in the embodiment and detailed design phase.

1.6 Research Contribution

The research is part of an ongoing project to design and develop RM systems for the DEMO FPP as part of the EUROfusion programme (a part of Horizon Europe) between multiple research consortiums. This work contributes to de-risking the DEMO FPP maintenance equipment explicitly designed to perform maintenance tasks remotely in harsh environments (radiation, excess heat, magnetic field, dynamic loads), increasing availability. The economic viability of the entire lifecycle of FPP depends on availability which extrapolates to a commercially viable FPP.

1.7 Thesis Structure

The rest of this work is organised as the DRM framework shown in Figure 3. Chapter 2 describes the research clarification, which conducts a high-level literature review and derives requirements for risk minimisation. Chapter 3 develops a new design methodology that supports risk minimisation based
during function structure establishment. Chapter 4 introduces a study case of designing one part of the hexapod crawler using the developed methodology. Chapter 5 evaluates the risk minimisation solutions by MATLAB simulation. Finally, chapter 6 and 7 summarises and concludes the thesis by discussing the effectiveness of the solutions and design methodology used in the thesis.
2 RESEARCH CLARIFICATION

This chapter presents a high-level literature review of the In-BioShield hardware components and examines requirements for risk minimisation.

2.1 Literature Review and Product Benchmarking

2.1.1 In-Bioshield Component Description

The In-Bioshield area is a region inside FPP, beginning at the first wall1 and reaching the Bioshield layer. Its location and components are illustrated in Figure 4.

In Figure 4, the green parts are the Vacuum Vessel, where the plasma ring is formed. The Vacuum Vessel covers the ring and works as a neutron shielding for the magnet system (blue component). The magnet system comprises multiple coils in many directions (poloidal, toroidal and central), generating the magnetic field to control the plasma inside the tokamak. These structures are covered and supported by the Cryostat and Thermal Shield (grey).

---

1 According to [39], the first wall is the blanket’s front-facing, removable components built to withstand heat flux from the plasma. These highly sophisticated components consist of beryllium tiles that are joined with 316L (N) stainless steel and an alloy of copper.
The In-BioShield component is categorised as a hierarchy structure, shown in Figure 5. Based on the DEMO maintenance objectives and requirements, the In-BioShield maintenance strategy includes the maintenance of magnets and containment structures. Each one consists of the corresponding sub-components. The specific design of the In-Bioshield component is not finalised yet. Some components are partially inherited from ITER, and some are newly designed.

![Figure 5 In-Bioshield components structure](image)

The environmental conditions for the In-BioShield component during maintenance are demonstrated in Table 1. In shutdown conditions, the temperature, radiation, and magnetic remain high and potentially impact maintenance equipment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnets</th>
<th>Vacuum Vessel</th>
<th>Thermal Shield</th>
<th>Cryostat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>20°C</td>
<td>20°-100°C</td>
<td>20°C</td>
<td>20°C</td>
</tr>
<tr>
<td>Radiation level</td>
<td>0.001 – 100 Gy/hr</td>
<td>0.1 – 100 Gy/hr</td>
<td>0.01 – 0.001 Gy/hr</td>
<td>0.01 – 0.001 Gy/hr</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.01 – 0.04 T</td>
<td>0.04T</td>
<td>0.01 – 0.04 T</td>
<td>0.01T</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>Dry air</td>
<td>Pressurised water</td>
<td>Dry air</td>
<td>Dry air</td>
</tr>
<tr>
<td>SIC Classification</td>
<td>N/A</td>
<td>SIC-1</td>
<td>N/A</td>
<td>SIC-1</td>
</tr>
</tbody>
</table>
2.1.2 DEMO Maintenance Overview

Maintenance is an administrative and technically coordinated activity that involves keeping the site facilities, infrastructures, systems, and components in good working order through preventive and corrective actions and statutory/safety inspections [7]. In the DEMO context, many maintenance activities include in-service inspection, in/ex-situ, corrective/ preventive, condition-based, or palliative.

Due to the harsh environment, all maintenance activities are performed remotely. The RM method uses automated systems and robots which humans control from a far distance. Although hazards that directly affect operators will be eliminated by employing the RM system, risks still exist from the surrounding environment and could potentially impact equipment hardware.

These are DEMO challenges, which are constrained to:

- **Space**: there are many confined spaces between In-BioShield components leading to impacts and collisions, enhancing dynamic forces
- **Environmental conditions**: harsh environment can be seen in Table 1, including high radiations levels, magnetic field, pressure and high temperature
- **Convoluted access Routes**: there are not many entrances to the In-BioShield area. They are distributed from several locations on the BioShield wall
- **Heavy loads**: most In-BioShield components have a massive size and weight, up to 80 tonnes or even 12 metres long, enhancing resonance

These challenges required the RM system to have enough flexibility and manoeuvre. Moreover, the system shall be capable of handling high loads and resisting extreme conditions.

2.1.2.1 Maintenance Scenarios

The In-BioShield maintenance scenario consists of 3 main steps: deploy the RM equipment, perform an inspection (visual, surface, volumetric, flow or leak test), and in-situ repair or replacement, which are shown in Figure 6. The specific type of inspection depends on the In-BioShield component being investigated. Finally, the system executes the remaining in-situ repair or replacement steps if faults or defects are detected.
The maintenance scenarios include the maintenance strategies, which have:

- **Scheduled vs Unscheduled**: the scheduled maintenance is the hardware inspection and repair performed within a fixed timeframe (example: weekly, biweekly, or monthly); the unscheduled maintenance occurs when In-bioshield hardware is down unexpectedly.

- **Preventive vs Corrective**: corrective maintenance aims to restore the failed hardware as soon as possible. Meanwhile, the goal of preventive maintenance is to prevent the hardware from future unexpected failures or downtime.

![Figure 6 Maintenance scenarios](image)

Each maintenance task performed by the RM system is a permutation of maintenance strategies in Figure 6. For instance, unscheduled corrective maintenance requires more effort and complexity due to downtime of the plan than scheduled with preventive action. The detail of permutations is still under development, but it is essential to be considered during system designs.

**2.1.2.2 Review of Potential In-Bioshield RM Systems**

The deployment system is the baseline to deploy and perform RM activities inside the In-Bioshield area, including the deployment equipment and additional infrastructures. During the work at VTT, several deployment systems for the In-Bioshield RM system are reviewed under the hierarchy structure in Figure 7. There are four applicable systems: rail-based, crawler, airborne, and arm-based. The crawler system is divided into five sub-groups.
Figure 7 Deployment system for consideration

**Rail-based system**

A rail-based system works with a network of rails set along the working space in the In-Bioshield. The type of rail could be a monorail or dual rail with at least a carriage running. Using rack and pinion aside from rail track for incline terrains is suggested. Rail-based systems have an advantage in carrying high loads with stability. However, fixed rail networks make them less flexible than other deployment systems.

**Airborne system**

The airborne system is a deployment method that involves at least a flying object, typically a drone. Drones are equipped with a caged frame to prevent collisions during movements and are useful for inspections in nuclear power plants. The airborne system has advantages in its lightweight and manoeuvrability. In contrast, it is only suitable for inspection; equipping it with an arm manipulator or other devices indirectly increases its weight and size.

**Arm-based system**

The arm-based systems are the deployment methods in which RM equipment is delivered to the point of work on a cantilevered structure supported at one end. Three main types of the arm-based system could be used to deploy RM equipment into the In-bioshield area: articulated arm, vertical mast or vertical mast and boom. The arm-based systems are good at delivering good dexterous and stable work performance but are limited by their space-consuming size. In addition, deploying the arm-based system requires additional deployment methods, such as infrastructures or a single aperture.
Crawler system

Crawler systems are mobile robots travelling freely along different terrains such as flat, convex or concave surfaces. The term “crawler” also implies its climbing capabilities. The crawler system in this work consists of two main functions – locomotion and adhesion mechanism, as given in Figure 8. Each combination between locomotion and adhesion mechanism gives a different crawler system with advantages and disadvantages.

![Crawler System Diagram]

**Figure 8 Crawler structure**

Crawler System - Spider robot

Various types of crawlers based on the concept in Figure 7 were reviewed during the benchmarking phase at VTT, including common ones used in the market and those under research. Due to its construction, the spider robot (hexapod crawler) is chosen as a study case model for risk minimisation in this thesis.

The hexapod crawler robot belongs to the legged robot, which uses legs for locomotion. The robot has six legs, and the foot can be configured with magnetic adhesion or a suction vacuum module to climb over various surfaces. Though this robot type is not being used commercially due to complex control algorithms, it has the potential to move over rugged or narrow terrains by adjusting its height flexibly.

Well-known research on this robot is by Marko Bjelonic [8]. The research offers locomotion improvement for the Weaver robot by using a hierarchical controller, making it able to move in unstructured and uneven terrains.
The system's concept diagram of the hexapod was drawn based on the kinematic of the hexapod and the conventional 6 Degree of Freedom manipulator arm, shown in Figure 10. This diagram shows how the Weaver robot can be re-designed to suit the In-BioShield context. It has an arm manipulator to perform maintenance tasks and adhesion mechanism modules integrated with its legs to climb over complex infrastructures. This concept idea is similar to the existing Boston Dynamic dog robot.
2.2 Identifying Requirements for Risk Minimisation

2.2.1 Inbioshield Design Requirements

General requirements for the In-Bioshield maintenance system are gathered during the DEMO project work and shown in Table 2. These requirements are general, and the number of components is divided into segments. Preliminary risks can be seen under requirements with high priorities.

Table 2 Design requirements

<table>
<thead>
<tr>
<th>ID</th>
<th>Requirement statement</th>
<th>Type</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-InBS-1</td>
<td>The In-BioShield System shall deploy RM tools with payloads of up to 10 tons</td>
<td>Requirement</td>
<td>High</td>
</tr>
<tr>
<td>REQ-InBS-2</td>
<td>The In-BioShield System shall visually inspect a minimum of 70 components</td>
<td>Requirement</td>
<td></td>
</tr>
<tr>
<td>REQ-InBS-3</td>
<td>The In-BioShield System shall conduct the surface inspection for a minimum of 48 components</td>
<td>Requirement</td>
<td></td>
</tr>
<tr>
<td>REQ-InBS-4</td>
<td>The In-BioShield System shall conduct the volumetric inspection for a minimum of 32 components</td>
<td>Requirement</td>
<td></td>
</tr>
<tr>
<td>REQ-InBS-5</td>
<td>The In-BioShield System shall conduct flow inspection for a minimum of 16 components</td>
<td>Requirement</td>
<td></td>
</tr>
<tr>
<td>REQ-InBS-6</td>
<td>The In-BioShield System shall conduct leak testing for a minimum of 16 components</td>
<td>Requirement</td>
<td></td>
</tr>
<tr>
<td>REQ-InBS-7</td>
<td>The In-BioShield System shall conduct in-situ repair for a minimum of 70 components</td>
<td>Requirement</td>
<td></td>
</tr>
<tr>
<td>REQ-InBS-8</td>
<td>The In-BioShield System shall replace a minimum of 70 components</td>
<td>Requirement</td>
<td></td>
</tr>
<tr>
<td>REQ-InBS-9</td>
<td>The In-bioshield System shall operate within temperatures from 20°C to 100°C</td>
<td>Constraints</td>
<td>High</td>
</tr>
<tr>
<td>REQ-InBS-10</td>
<td>The In-bioshield System shall operate within radiation levels between 0.001 and 100 Gy/hr</td>
<td>Constraints</td>
<td>High</td>
</tr>
<tr>
<td>REQ-InBS-11</td>
<td>The In-bioshield System shall operate in dry air at atmospheric pressure</td>
<td>Constraints</td>
<td>High</td>
</tr>
<tr>
<td>REQ-InBS-12</td>
<td>The In-bioshield System shall operate in pressurised water</td>
<td>Constraints</td>
<td>High</td>
</tr>
<tr>
<td>REQ-InBS-13</td>
<td>The In-bioshield System shall operate within the magnetic field from 0.01 to 0.04T</td>
<td>Constraints</td>
<td>High</td>
</tr>
<tr>
<td>REQ-InBS-14</td>
<td>The minimum operational space that the system can work is 118mm</td>
<td>Constraints</td>
<td>High</td>
</tr>
</tbody>
</table>

2.2.2 Design Drivers

Aside from the requirements, four design perspectives must also be considered for a comprehensive RM system. These are the design goals, key risks, boundary conditions, and assumptions. These five perspectives set the motivation for the In-Bioshield RM system's design and translate into the design
drivers. The Design Driver (DD) is a factor that motivates or stimulates the design process. It identifies the design’s objectives and limitations, which can be interpreted as latent needs for the intended product. The design driver of the In-BioShield RM system is illustrated in Table 3.

Table 3 Design Drivers

<table>
<thead>
<tr>
<th>Group</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Goal</td>
<td>Develop the remote maintenance systems to operate in the In-Biosisield environment with minimum failure to ensure maximum availability of the FPP.</td>
</tr>
<tr>
<td>REQUIREMENTS</td>
<td>The In-Biosisield System shall deploy RM tools with payloads of up to 10 tons</td>
</tr>
<tr>
<td></td>
<td>The Remote Maintenance System shall conduct inspection of In-Biosisield components</td>
</tr>
<tr>
<td></td>
<td>The Remote Maintenance System shall conduct testing of In-Biosisield components</td>
</tr>
<tr>
<td></td>
<td>The Remote Maintenance System shall conduct in-situ repair for In-Biosisield components</td>
</tr>
<tr>
<td></td>
<td>The Remote Maintenance System shall replace In-Biosisield components</td>
</tr>
<tr>
<td></td>
<td>Maximum operation temperature is 100°C</td>
</tr>
<tr>
<td></td>
<td>The maximum operation radiation level is 100 Gy/hr</td>
</tr>
<tr>
<td></td>
<td>The Remote Maintenance System shall operate in dry air at atmospheric pressure</td>
</tr>
<tr>
<td></td>
<td>The Remote Maintenance System shall operate in pressurised water</td>
</tr>
<tr>
<td></td>
<td>The maximum operation magnetic field is 0.04T</td>
</tr>
<tr>
<td></td>
<td>The minimum Operation space for a task is 118mm</td>
</tr>
<tr>
<td>Key Risks</td>
<td>Accurate positioning of hardware</td>
</tr>
<tr>
<td></td>
<td>Advanced control system</td>
</tr>
<tr>
<td></td>
<td>Manoeuvring RM equipment through confined space/ orientations</td>
</tr>
<tr>
<td></td>
<td>Dynamic loads</td>
</tr>
<tr>
<td></td>
<td>Reliable performance under dynamic/seismic input loads</td>
</tr>
<tr>
<td></td>
<td>Capabilities to deliver good maintenance performance for In-biosield’s hardware</td>
</tr>
<tr>
<td></td>
<td>Maintenance devices failing and either not being recoverable or not failing in a safe state condition</td>
</tr>
<tr>
<td></td>
<td>Capabilities of commercial off-the-shelf (COTS) components</td>
</tr>
<tr>
<td></td>
<td>Modified COTS/ bespoke components</td>
</tr>
<tr>
<td></td>
<td>Capable of handling self-recovery and rescue mission</td>
</tr>
<tr>
<td></td>
<td>Space</td>
</tr>
<tr>
<td></td>
<td>Insufficient space to transport maintenance equipment</td>
</tr>
<tr>
<td></td>
<td>The system can work in confined spaces</td>
</tr>
<tr>
<td>Boundary Condition</td>
<td>The In-Biosisield area is from the first wall of the Bio-shield to the first wall of the vacuum vessel</td>
</tr>
<tr>
<td></td>
<td>Functionalities constrained by the geometry of the In-Biosisield hardware</td>
</tr>
<tr>
<td></td>
<td>Failsafe design approach</td>
</tr>
</tbody>
</table>
The maintenance scenarios consist of 3 main steps: deploy RM equipment, perform inspections (consists of visual, surface, volumetric, flow, leak-test), replace, and in-situ repair.

The maintenance strategy is bounded by schedule vs unscheduled maintenance.

The maintenance strategy is bounded by corrective vs preventive maintenance.

Implementation of appropriate technologies.

<table>
<thead>
<tr>
<th>DESIGN ASSUMPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance of the In-Bioshield component takes place during shutdown condition</td>
</tr>
<tr>
<td>The construction of the In-BioShield component comprises the use of specific materials</td>
</tr>
<tr>
<td>There are no obstructions to penetrating the In-BioShield</td>
</tr>
<tr>
<td>The In-BioShield components are assigned with SIC classification from SIC-1 to SIC-3</td>
</tr>
</tbody>
</table>

### 2.2.3 Risk Minimisation Requirements

Several key risks are observed in the design drivers in Table 3. In order to cover risks from many perspectives, they shall be categorised into three groups: failure modes, situational and quality risks, as shown in Figure 11.

![Figure 11 Main risk elements](image)

A failure mode is a way a product’s component, assemblies or subsystems might fail. Failure modes are typically derived through relevant historical data. In the DEMO project, failure modes can be referred to from similar applications such as fission nuclear power plants or high-temperature vessels. Failure modes could be avoided by optimising mechanical design or selecting appropriate materials.

Situational risks come from unaware scenarios that, during maintenance activities, the RM system could encounter. These are the most challenging ones. For instance, maintenance equipment can be dropped during handling and damage the power plant component. Situational risks could be mitigated by improving the product’s precision, payload, or control algorithms.
Aside from failure modes and situational risks, quality risks are related to the effectiveness of the In-BioShield maintenance. It reflects how the product impacts the production performance of the fusion power plant. A good illustration is that the In-BioShield RM system takes too long to complete maintenance tasks, resulting in poor key indicators such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), or Machine Availability (MA). These problems can be solved by developing better maintenance processes and increasing maintenance tools’ performance.

When the details of the products have not yet been shaped, the failure mode is one of the simple approaches in early design. However, designers can consider the other two risk types during later embodiment or detailed design phases. In this research, the failure mode is made an integral part of activities in the early design stage. Failure modes can be extracted from brainstorming meetings or information from historical data, requirements, or from the design driver.

Failure modes in this thesis are extracted from the requirements and design driver. Table 4 presents the requirements considered for risk minimisation. The Risk Minimisation Requirements (RMR) are defined by coupling the design goals, requirements, key risks, boundary conditions, and assumptions - the five fundamental views for the In-Bioshield RM system's design. The RMR identifies the Risk factors implemented in the design for minimum risks in this thesis.

<table>
<thead>
<tr>
<th>ID</th>
<th>Requirement</th>
<th>Risk Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>RREQ-InBS-1</td>
<td>The system shall work properly within a maximum temperature of 100°C</td>
<td>High Temperature</td>
</tr>
<tr>
<td>RREQ-InBS-2</td>
<td>The system shall work properly within a maximum radiation level of 100Gy/hr</td>
<td>Radiation</td>
</tr>
<tr>
<td>RREQ-InBS-3</td>
<td>The system shall work properly within a maximum magnetic level of 0.04T</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>RREQ-InBS-4</td>
<td>The system shall be capable of working under dynamic and seismic input loads</td>
<td>Dynamic Forces</td>
</tr>
<tr>
<td>RREQ-InBS-5</td>
<td>The system shall operate properly in the pressurised water</td>
<td>Pressure</td>
</tr>
</tbody>
</table>
3 DESIGNING FOR MINIMUM RISK METHODOLOGY

3.1 State of The Art

3.1.1 Function Structure Diagram

Starting with the fundamental concept that views energy, matter, and information as a basic representation of technological artefacts, Pahl and Bietz [9] describe that all technical systems involve energy, signal, and material conversions. Based on the main flow of this conversion, the developing system can be categorised into the technical system, apparatus, or devices [9].

The product's design is constrained by requirements, which can be stated in terms of certain inputs and outputs. Following the abstraction of these inputs and outputs, the overall function of a system under a single black box can be derived (Figure 12), which is a graphical representation describing the primary goal of the product under the conversions of energy, material, and signal. Subsequently, the black box is broken down into smaller subfunctions. These subfunctions depend not only on the requirements but also on any previous function blocks that they could associate. Each subfunction uses a syntax comprised of a verb and object to describe its function and stick to the product’s main flow, showing the logic sequence of how it works. Combining these sub-functions under block diagrams and ensuring the overall function is met is called a Function Structure Diagram (FSD).

![Figure 12 Black box representation in conceptual design](image)

The FSD has a long history of applications in engineering design. Ulrich and Eppinger [10] demonstrated the use of FSD as a fundamental tool for searching for solutions internally and externally. Several techniques can be implemented to produce concepts, such as classification trees or combinations when solutions are discovered and listed. Alternatively, according to Ashby [11], the FSD provides a methodical approach to evaluating design options, where concepts are concatenated from working principles.

A product or system is modelled abstractly in the initial modelling task, as shown in the black box in Figure 12. The function variables with input/output flow allow for focusing on the most outstanding overall need of the system. In a complex system design process, it is often convenient to view some input/output in terms of generalised variables. For instance, Coatanéa [12],
Brace et al. [13], and Kroll et al. [14] in their work abstracted generalised variables in terms of forces (including moments) and generalised displacements. In this thesis, the black box for a complex system is shown in Figure 13, with generalised variables abstracted in terms of the risk factors from Table 4.

![Figure 13 Black box model for the design of a complex system](image)

### 3.1.2 Risk Minimisation in Design

Many researchers have recently reviewed and considered risks in engineering design. According to Pahl and Beitz [9], risks are defined as uncertainties that might happen from a technical or economic perspective. Both authors suggested that integrating them into conceptual or embodiment phases would be a cost-saving way to cope with risks. However, their work mostly takes examples of risk minimisation during embodiment design [9], and little has been focused on the conceptual phase, especially in requirements and function analysis.

Tummer et al. [4] proposed a new methodology to accomplish functional design with minimum failure modes, called the Function-Failure Design Method (FFDM). This approach aims to get a function-failure matrix (denoted by EF), which is derived as a multiplication between a function component (denoted by EC) and a component-failure (denoted by CF) matrix. As a result, designers could achieve a failure mode related to each function and solve it by either using the concept generator [15] or the conventional design approach that uses brainstorming to generate and evaluates concept variants. Later, Katie et al. [5] developed a new Risk in Early Design (RED) method as an extension of the FFDM methodology. The RED technique calculates the likelihood and consequences as a quantitative reference for designers to evaluate the seriousness of function failure. There are two kinds of mapping with different pros and cons for each likelihood and consequence. The results of this framework are represented under a risk summary, similar to a risk fever chart.

The FFDM has the advantage of systematically revealing risks for each component; meanwhile, the RED help to assess its impact. However, these approaches become hard to trace if the size of the matrix elements increases.
significantly and somehow increases the design’s complexity. Furthermore, identifying risks under mathematical formulas becomes challenging to visualise the interrelationship and consequences between the product’s inputs, risk elements and function blocks in the FSD. In addition, performing FFDM and RED depends on a strong knowledge base of historical failure modes data, which is not viable for developing a new product type.

3.2 Background to Risk Analysis

Design research aims to increase knowledge and support design processes. However, without technical expertise, the design itself will lack practical experience. Therefore, this section reviews and analyses the physical mechanisms behind risks identified in risk minimisation requirements (Table 4).

3.2.1 High Temperature - Heat

There are numerous forms that energy can exist. Heat or thermal is one form of it. From a physical perspective, thermal energy results from the vibrations of atoms and molecules of a substance. The higher the temperature, the faster and more chaotic the molecules move.

During movements and maintenance operations, heat may come from various sources. Direct heat can be easily observed from the ambient environment, affecting the In-BioShield RM system. Other sources like internal heat caused by the electrical components, friction between mechanical parts or heat generated by welding tasks are indirect risks contributing to the overall system performance. High temperatures make metal parts expand. Thermal expansions not anticipated during design phases lead to collisions between assemblies and connection joints, causing high stresses and structural failures. A combination between elevated temperatures and loads under long periods could cause creep and stress relaxation. The mechanism of this phenomenon will be clearly explained in section 3.2.3.

![Figure 14 Mechanisms of Heat Transfer](image)

Generally, heat is transferred by three mechanisms: conduction, convection and radiation, as shown in Figure 14.
3.2.1.1 Heat Transfer by Conduction

Conduction is the transfer between more energetic and less energetic particles [16]. Conduction occurs in solids, liquids, and gases. In solids and gases, random, vibrational, and rotational motions generate kinematic energy. For solids, heat conduction is caused by two factors: the energy transferred by the free flow of electrons within the solid and the lattice vibrational waves created by the vibrational motions of the molecules placed at relatively fixed positions systematically [16]. As a result, the thermal conductivity of solids and gases is lower than metal. Meanwhile, a material with a better molecule arrangement in the lattice will have higher thermal conductivity between solids (for instance, diamond is higher than aluminium). The rules of this arrangement are considered a principle for selecting a thermal insulation layer.

Consider a walled system in Figure 15, which is covered by an insulation layer. The insulation layer has a thickness of t and an area of A (m²). The temperature of the environment (Ta °K) is greater than the internal temperature of the system (Ti °K). The heat tends to transfer from the ambient environment to inside the system, as shown in the following equation:

\[ \dot{Q}_{\text{cond}} = kA \frac{T_a - T_i}{t} \]  

(2)

In this equation, k is the thermal conductivity of the material with a unit of W/m · K and \( \dot{Q}_{\text{cond}} \) is the rate of heat conduction (W). When thickness t → 0, the equation (3) becomes Fourier’s law of heat conduction, as given:

\[ \dot{Q}_{\text{cond}} = -kA \frac{dT}{dt} \]  

(3)
3.2.1.2 Heat Transfer by Convection

The second mechanism is convection, which transfers heat between solid surfaces and gas or liquids. Convection is a combined effect between conduction and fluid motion, but more depends on fluid. The heat transferred from hot electrical (solid) surfaces to air (gas) is considered convection. The rate of heat conduction (W) for the convection mechanism is expressed by:

\[ \dot{Q}_{\text{conv}} = h A (T_s - T_f) \]  

\( h \) (\( W/(m^2 \cdot K) \)) convection heat transfer coefficient  
\( A \) (\( m^2 \)) the surface area where convection heat transfer occurs  
\( T_s \) (K) the surface temperature of solid  
\( T_f \) (K) the temperature of fluid/ gases

3.2.1.3 Heat Transfer by Radiation

The final heat transfer mechanism is radiation. Every object emits an amount of thermal radiation that correlates with its temperature. It is the energy emission of electromagnetic waves (photons) from higher energy to lower energy levels. One good illustration of this is the working principle of a thermal infrared camera, which uses sensors to pick up radiation. Identifying the wavelengths can give users an approximation temperature of the measuring objects.

The rate of heat conduction for thermal radiation of an object during emission to the environment is derived through the Stefan-Boltzmann law:

\[ \dot{Q}_{\text{rad}} = \varepsilon \sigma A (T_{s'}^4 - T_{\text{surr}}^4) \]  

\( \varepsilon \) emissivity of the surface (0 \( \leq \varepsilon \leq 1 \))  
\( \sigma = 5.67 \times 10^{-8} \) \( W/m^2 \cdot K^4 \) Stefan-Boltzmann constant  
\( T_{s'} \) (K) the absolute temperature of the emitting surface  
\( T_{\text{surr}} \) (K) the absolute temperature of the surrounding environment

3.2.1.4 Rate of Heat Transfer

Equations (2), (3), (4) and (5) represent the rate of heat transfer, which is the amount of heat transferred in a unit of time. To find the heat energy, we can calculate from the equation below
Another formula to calculate the heat energy a system absorbs is expressed by

\[
Q = m c_p \Delta T
\]

\[\text{(7)}\]

\(m\) (kg) weight of the object
\(c_p\) (\(\frac{J}{kg \cdot K}\)) specific heat capacity of the substance
\(\Delta T\) (K) temperature difference

In the real world, when a system operates in an area, the total heat energy that the air inside the system receive is a sum of conduction, convection and radiation energy from the outside environment. Aside from these powers, the internal air receives additional power from operating electrical components under heat loss. The total heat energy of this heat loss is called excessive energy generated by the system, derived through the power efficiency formula:

\[
Q_e = P(1 - \eta_e) t + Q_2
\]

\[\text{(8)}\]

\(P\) (kg) Total power capacity of the electrical system
\(\eta_e\) power coefficient of the electrical system
\(t\) (s) running time
\(Q_2\) auxiliary heat energy from the system (friction, movement)

The total energy the system receives must equal the energy it emits through the environment, which satisfies the energy conservation law. Therefore, by adding a cooling system that represents the system’s heat emission and equations (3) to (9), we could approximate the heat energy and temperature at the system ends up.
An active cooling function block demonstrates the use of pneumatic air and fans to cool down electrical parts inside the system. Figure 16 illustrates the idea for this model. Cool pneumatic air is blown and distributed equally by fans. The heat inside the system is then exchanged and goes outside of the system through an umbilical cable. The mathematical model of this function block is expressed through the equation below following the first law of thermodynamics:

\[ \dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system} = 0 \]  

(9)

The net energy transfer by heat, work, and mass is known as \( \dot{E}_{in} - \dot{E}_{out} \). The change in internal, kinetic, and potential energy is represented by the term, \( \dot{E}_{system} \) in this context [16]. Since internal parts of the system are cooled steadily by a heat exchanger, this system is considered a steady-flow system and \( \dot{E}_{system} = 0 \). Transform and substitute equation (9) to the RM system context; we have:

\[
\begin{align*}
\dot{E}_{in} &= \dot{E}_{out} \\
Q_e + Q_i + \dot{m}h_1 &= \dot{m}h_2 \\
Q_e + Q_i &= \dot{m}c_p(t_i - T_i)
\end{align*}
\]

(10)

\( h_1, h_2 \ (kg) \) enthalpy of the airflow in and out
\( \dot{m} \) the mass flow rate of the exchange air

By changing the mass flow rate \( \dot{m} \) and temperature \( T_{in} \) of the input air, we could have the desired temperature of the system during the steady phase \( i_{in} \). This is also equal to the air temperature inside the system. These parameters are fundamental inputs for the design phases of the system.

3.2.1.5 Design Consideration for Thermal Risk Mitigation

Designing for high temperatures must follow heat transfer principles. Thermal risks cannot be prevented entirely, but the thermal management approach can mitigate them [17]. In this thesis, risk reduction for thermal is divided into three progressive steps:

- **Design for thermal insulation layers**: these layers efficiently reduce heat transfer from the outside environment to the internal area of the system. Insulation layers slow down the temperature increment and extend the work time of the system in worst-case scenarios before the temperature is elevated to critical thresholds.

- **Design for thermal exchange**: after the first step, although the temperature increment is slowed down due to insulation layers, internal heat caused by electrical parts during working could cause
different thermal distribution inside the system. The thermal exchange is required to maintain an even temperature throughout the system. Several cooling techniques using extra energy, such as pneumatic, could also be applied.

- **Design for thermal expansion**: this is the last step of thermal risk mitigation. Temperature increment after thermal insulation and exchange makes materials expand. Calculating expansion length and tolerating it in design parts help avoid collision risks in assembly.

### 3.2.2 Thermal Expansion

Solids or metals tend to expand when temperature increases. It can be explained that atoms and molecules vibrate and move faster during temperature increments, creating longer distances between them. Thermal expansion is a characteristic of materials and is represented by the thermal expansion coefficient $\alpha$. The relationship between material expansion and temperature is expressed by

\[ \frac{dL}{L} = \alpha dT \]  

Equation (11) is the fundamental equation of thermal expansion. In practice, two equation forms are used to calculate thermal expansion. The linear expansion of material under steady temperature changes, which is the simplest form of equation (11), is defined as:

\[ \Delta l = \alpha \cdot l \cdot \Delta T \]  

$\Delta l$ changes in length by thermal expansion  
$\alpha$ Linear thermal expansion coefficient  
$l$ the original length of material  
$\Delta T$ mean temperature difference of the body

An alternative way is more complex but describes the changes in length more accurately than the linear method in equation (12) by integrating equation (11). The results show that the changes by thermal expansion are an exponential function of temperature [18], which is

\[ L = L_0 e^{\bar{\alpha}(T - T_0)} \]  

$T$ target temperature  
$T_0$ initial temperature  
$\bar{\alpha}$ average thermal expansion coefficient between $T$ and $T_0$
The thermal expansion causes thermal stress between different materials or in assembly joints. These stresses could result in plastic deformation or fracture depending on additional heating factors such as material types and restrictions. Thermal stress is formulated by

\[
\sigma_{\text{thermal}} = E \cdot \varepsilon_{\text{thermal}} = E \cdot \Delta L
\]

\(E\) Young’s modulus of material
\(\varepsilon_{\text{thermal}}\) Thermal strain
\(\Delta L\) length changes caused by thermal expansion

If the final temperature is more significant than the initial temperature \((\Delta T > 0)\), the thermal stress exerts compression forces on the material’s body, otherwise tensile. Therefore, thermal expansion risks can be anticipated and minimised by adding expansion clearances and using alternative support types. Clearances calculation can follow equations (12) and (13). For support type, materials tend to move longitudinally in the direction of thermal expansion [17]. This movement is dangerous for fixed joints in conventional mechanical design. As a result, rigid, flexible and sliding supports are good options to avoid these risks.

### 3.2.3 Creep

When a material is loaded continuously under constant stress, it gradually deforms. This process is known as creep. As a result of this phenomenon, in high temperatures, tensile and yield strength could not be used in conventional ways.

The homologous temperature was used to determine what temperature material could begin to creep. Most creeps when the homologous temperature is more significant than 0.5, as follows:

\[
T_{\text{homo}} = \frac{\text{testing temperature}}{\text{melting temperature}} > 0.5
\]

The homologous temperature value shown in equation (15) depends on the material (for instance, \(T_{\text{homo}} = 0.4\) for stainless steel). Creep phenomenon often goes through four stages, as shown in Figure 17:

- **First stage – primary creep**: this is a region of decreasing creep rate. In this stage, the creep rate decreases as the material’s resistance increase under its deformation.

- **Second stage – secondary creep**: at this stage, the creep rate is almost constant, showing a balance between the competing processes of strain hardening and recovery, called steady-state creep. The
average number of values in this stage is called the minimum creep rate or creep rate

- **The third stage – tertiary creep**: occurs when we have high stresses under high temperatures. This stage relates to and is associated with metallurgical changes

The creep mechanism is divided into four groups. Each material’s creep belongs to one of these mechanisms depending on stress and temperature factor. Four groups can be summarised below:

- **Dislocation glide**: thermal activation causes dislocations to move along slip planes and overcome obstacles.
- **Dislocation creeps**: a thermally aided mechanism involving the diffusion of vacancies allows dislocation to pass across obstacles.
- **Diffusion creeps**: involves the movement of vacancies and interstitials inside the crystal under applied stress.
- **Grain boundary sliding**: slipping granules pass one another

![Figure 17 Three stages of creep [19]](image)

In finite element software, many models have been used to model primary or secondary creep deformation. This thesis mainly uses the Bailey-Norton model due to its simplicity and can be approximated using experimental data. The creep rate $\dot{\varepsilon}_c$, following the bailey-Norton model is defined as follows:

$$\dot{\varepsilon}_c = C_1 \sigma^2 e^{-\frac{C_3}{T}}$$  \hspace{1cm} (16)

- $C_1, C_2$ the material constant depends on the materials ($C_1 > 0$)
- $C_3$ Material constant defining the creep temperature dependency
- $T(K)$ Absolute temperature
From an early design perspective, designers can choose one of two creep-rate limits when designing parts. First, stress that produces a creep rate of 0.0001% per hour or 1%/10000h or $2.8 \times 10^{-10} \text{s}^{-1}$, which is typically considered in jet-engine alloy design. Secondly, stress produces a creep rate of 0.00001% per hour or 1%/100000h or $2.8 \times 10^{-11} \text{s}^{-1}$, being used widely in steam turbine design or similar equipment applications [19].

Activation energy, creep strength and rupture strength can be derived depending on the creep test experiments to find material constants in the Bailey-Norton model. The working stress under specific temperatures can be approximated with a safety factor. Nevertheless, a lifetime of material can be predicted and verified through calculation software.

These are possible methods by that creep in materials can be anticipated during the design. However, the most critical factors are material selection and load distributions under temperature and time.

### 3.2.4 Stress Relaxation

Any mechanical preload parts such as springs, bolts, tension wires, or shrink fits will produce an overall strain $\varepsilon_T$ under initial stress $\sigma_0$. Due to changes in modulus of elasticity $E$ with temperature and creep factor, the initial stress of preloads decreases when the temperature rises over time, but the strain is still constant. This phenomenon is called stress relaxation.

![Figure 18 Maxwell Model](image)

Stress relaxation occurs in various materials and is connected with the creep phenomenon. The stress of preloading parts after being reduced by relaxation can creep in elevating temperature. The combination of these factors would lead to a significant drop in initial preload.

The Maxwell is the simplest stress relaxation model; it describes stress relaxation in materials with both elastic and viscosity properties (Figure 18). Elastic strain $\varepsilon_p$ is represented by a dashpot connected continuously with a spring (strain denoted by $\varepsilon_e$). Total strain is derived as

$$\varepsilon_T = \varepsilon_e + \varepsilon_p$$

(17)
By taking mathematical transformations, equation (17) becomes

\[
\sigma = E_0 (\varepsilon_e + \varepsilon_p) e^{\frac{Et}{\eta}} = E_0 \varepsilon_T e^{\frac{Et}{\eta}} = \sigma_0 e^{\frac{Et}{\eta}} = \sigma_0 e^{t \tau}
\]  

(18)

\( \sigma_0 \) preload stress  
\( \sigma \) current stress  
\( t \) time  
\( \eta \) viscosity

Maxwell equation is suitable for predicting the stress relaxation of design parts. However, like the creep phenomenon, designing for stress relaxation requires empirical data. By comparing predicted values with relaxation data for a specific material, designers would see whether their material is suitable or determine replacement time for preload parts.

### 3.2.5 Nuclear Radiation

Nuclear radiation and electromagnetic radiation are two different types of radiation. Nuclear radiation is ionising radiation, the energy released as charged particles or electromagnetic waves. While wave characteristics like photons describe electromagnetic radiation, nuclear radiation is represented by particle characteristics. However, in nuclear radiation, gamma is one exception which is electromagnetic radiation but given off by a photon that escapes the particle (nucleus).

Figure 19 illustrates the types of nuclear radiation and their penetration strength. In general, it consists of 4 types:

- **Alpha (α) radiation**: when an atomic nucleus shoots out an alpha particle, it consists of 2 protons and two neutrons (helium missing electrons). Alpha radiation is a heavily charged particle and the heaviest one. It can easily be affected by magnetic fields
- **Beta radiation (β)**: is released when an atomic nucleus shoots out an electron. Beta radiation has better penetration than alpha, a particle penetrating 0.5cm of aluminium, and it is much lighter than alpha radiation
- **Gamma radiation (γ)** is not a particle; it is released when an extremely high-energy photon escapes the nucleus (or the nucleus emits light or wave). X-ray is similar to gamma but less energetic. Gamma radiation has no mass or no charge, and it has the highest penetration capabilities. It can penetrate through almost everything except lead materials
- **Neutron radiation**: is released by the emission of a neutron. Neutron radiation is the most dangerous type of radiation. It is a heavy
particle with no electric charge and can be prevented by water or paraffin.

Basic definitions such as absorbed, equivalent, and effective dose are used in the radiation context. Absorbed dose rate, denoted by \( D \) (\( \frac{Gy}{hr} \)) determines how much energy material is absorbed from ionising radiation. Equivalent dose rate \( (H\delta) \) and effective dose \( E \) with sievert unit (\( Sv \)) is a multiplication between absorbed dose rate with a tissue weighting factor, determining the biological effects of radiation on human tissues. Since the RM system replaces humans, the absorbed dose rate is more significant than the remaining two terms.

Nuclear radiation can come from many sources, both natural and manufactured. Irradiation refers to solid materials being damaged or degraded under radiation exposure. In order to avoid the effects of nuclear radiation, shielding or radiation-hardened electronics are considered.

### 3.2.5.1 Nuclear Radiation Shielding

Shielding techniques depend on the penetration capabilities of the radiation type to choose the necessary thickness and appropriate materials. In nuclear fusion, most radiation comes from alpha, beta and neutron radiations. Therefore, there is a rule of thumb to minimise it [20]

- **Slow the neutrons**: by using hydrogenous material: water, paraffin, and plastic. For high-speed neutrons, iron or lead are used in front of hydrogenous materials
- **Absorb the neutrons**: hydrogenous materials are practical and absorb these neutrons. Boron, iron or lead can be considered depending on the speed of neutrons
- **Absorb the gamma rays**: gamma rays produced by neutron capture, inelastic scattering and decay of activation products

The shielding equation for neutrons can be found in [20], which is given by

\[
D = B_u D_0 e^{-(\frac{\Sigma_E}{\rho}) \rho t}
\]  

- \(B_u\) build-up factor can be found in empirical data
- \(\Sigma_E\) mass attenuation coefficient \((cm^2/g)\)
- \(\rho\) density of material \((g/cm^3)\)
- \(D_0\) absorbed rate after shielding \((Gy/hr)\)
- \(D\) absorbed rate before shielding \((Gy/hr)\)
- \(t\) shield thickness \((cm)\)

In this equation, the build-up factor \(B_u\) is used to explain the contribution of scattered radiations caused by a broad beam or thick shield to the overall exposure rate. Shielding effectiveness strongly correlates with shield thickness. An increment in thickness could improve the shielding performance, but weight and size could also increase. Unfortunately, not so many materials are capable of shielding applications. Some common ones are concrete and lead, which have high density and are inapplicable to integrate with robots.

### 3.2.5.2 Nuclear Radiation Hardening

An alternative option aside from radiation shielding is to use radiation-hardened components. Radiation hardening makes electronic parts and circuits resistant to damage or malfunction by high amounts of ionizing, particularly in outer space or around nuclear reactors.

Instead of the conventional semiconductor wafers, hardened chips are frequently produced on insulating substrates, usually in silicon or sapphire insulator layer. There are typically three approaches for hardened radiation components: architecture, design or process. Architecture focuses on reducing redundancy on the component or board level. The design prioritises the implementation of isolation on the component layout. Lastly, materials, fabrication and processing techniques are used to enhance the performance of electrical components. Figure 20 shows an instance of IBM’s radiation-hardened component for space shuttles.
Radiation shielding or radiation-hardened electronics has their advantages and trade-offs. Combining radiation shielding layers and radiation-hardened electronics offers the best radiation resistance performances but indirectly increases the size of the product. Depending on the practical case, shielding or radiation-hardened components can be determined.

3.2.6 Magnetic Field

In the In-BioShield area, maintenance operations are assumed to occur during shutdown conditions. The magnetic field is estimated to be around 0.01-0.04T. This magnitude is relatively small and can be neglected. However, a permanent or low-frequency magnetic field could exist since In-BioShield is a giant structure with many coils covered. This could affect the performance of electrical components and exert magnetic forces on structures; therefore, risks from magnetic fields exist, and mitigation through magnetic shielding is essential.

There are three rules of thumb to reduce the magnetic field strength:

- Placing a barrier (shield) between the source and the area that needs electromagnetic fields to decrease
- Using a device or material that can diverge the electromagnetic field from the area
- Using other sources that can affect and reduce the magnetic field from emitters

Since the second and third rule is not always viable to perform, rule number one is prioritised. The barrier can be designed as shielding layers made from special materials that could help reduce magnetic fields. In order to construct this shield type, fundamental magnetic field theories should be understood clearly.

In general, a magnetic field is an invisible field around magnetic objects that applies a magnetic force to magnetism-sensitive materials. Magnetic fields can be produced by an electric current, a magnet or a charging electrical field.
A magnetic field can harm electronic devices, causing noises and unwanted forces to ferrous materials.

Magnetic fields have two primary effects: to exert a force on other magnets or magnetise other materials. These characteristics are expressed by magnetic field strength \( H \left( \frac{A}{m} \right) \) and magnetic flux density \( B \ (T) \). While \( B \) represents expert forces on other poles, \( H \) implies the capability to magnetise other materials. The relationship between these two terms is expressed by

\[
B = \mu H
\]

\( \mu \) permeability of a material

Equation (20) illustrates \( B \) and \( H \) under a medium. Permeability is a crucial term for shielding. It refers to a material or medium’s capacity to become magnetised when exposed to an external magnetic field. The difference between low and high-permeability materials is illustrated in Figure 21. To compare this characteristic of materials, absolute and relative permeability are used:

- **Absolute permeability (μ):** the permeability of the material. For vacuum, it is denoted by \( \mu_0 \)
- **Relative permeability (μr = \( \frac{\mu}{\mu_0} \)):** is a ratio between a material’s permeability and vacuum permeability, so it determines how strong the permeability of a material compared to a vacuum

![Figure 21 Illustration between low and high permeability material](image)

Magnetic shielding is often made of ferromagnetic materials with high permeability characteristics that can re-direct external magnetic fields, so there would be less field effect on the shielded internal component. Ferromagnetic materials’ permeability varies nonlinearly with H’s magnetic induction. The B-H curve describes this nonlinear behaviour in response to an applied magnetic field and is referred to during material selection. Permalloy sheets or mu-metal generate their internal magnetic field and are commonly used for commercial purposes.
Aside from materials, shield efficiency depends on the shield’s geometry (shape), thickness and layers. A shape perpendicular to the magnetic field often delivers better shielding. The thicker the shield layer, the more magnetic field it can resist. Finally, a magnetic shield usually consists of multiple layers, and an air gap between them significantly increases shield effectiveness.

A thickness for magnetic shielding can be approximated as follows

$$t = \frac{1.25 \cdot D_S \cdot H_0}{B}$$

(21)

- $t$: shield thickness (mm)
- $D_S$: physical dimension depicting the shield’s size. For a rectangular, it is the diagonal dimension, and for a cylinder, it is the diameter
- $B$: flux density (T)
- $H_0$: magnetic field strength to be shielded (Gauss)

Equation (21) is just a rough estimation only. The detailed design requires numerous iterations involving experiments, verification and optimisation for the shield. There are many ways to verify the effectiveness of a magnetic shield. One uses the attenuation ratio, which equals the original and shielded field strength ratio [22]. It is expressed by

$$A = \frac{\mu \cdot t}{D}$$

(22)

- $\mu$: permeability of a material
- $t$: shield thickness (mm)
- $D$: physical dimension depicting the shield’s size

One alternative way is using Shielding Effectiveness (SE) factor [23]. It is a ratio between the absolute value of the magnetic field

$$SE = 20 \log \left( \frac{|H^{inc}(r)|}{|H(r)|} \right)$$

(23)

- $H^{inc}(r)$: the magnetic field of the reference point without shielding
- $H(r)$: the magnetic field of the reference point with shielding

The efficiency of magnetic shielding can be evaluated using equations (23). The logarithm function is suitable for significant scaling. Equations (21) and (22) are appropriate to verify the estimated shield thickness and dimensions.
3.2.7 Vibrations

One of the most extreme risks from dynamic loads or vibration is seismic events which refer to external intense vibration events such as earthquakes or seismic waves. Under the vibration engineering view, this phenomenon is considered a harmonic excitation. Harmonic excitations are a typical source of external force applied to machines and structures [24]; they could lead to potential fatigue failures, high stresses or accelerations to the mechanical system.

A seismic event is characterised by its oscillation magnitude $A_0$ and angular frequency $\omega$ (rad/s). When a seismic event occurs, oscillation can be expressed by

$$A(t) = A_0 \cos(\omega t)$$

(24)

The acceleration of the seismic event is a derivation of equation (24):

$$A'(t) = -\omega^2 A_0 \cos(\omega t)$$

(25)

According to Newton’s law of motion, external forces caused by a seismic event are formulated as follows:

$$F_{\text{external}} = ma = -m\omega^2 A_0 \cos(\omega t)$$

(26)

Here, $m$ (kg) is the weight of the mechanical system. From vibration engineering [24], the equation of motion under an external cosine force applied to an undamped system can be represented by

$$m\ddot{x} + kx = F_0 \cos(\omega t)$$

(27)

Equation 27 is a non-homogenous second-order differential equation. In order to solve the solution is divided into two parts: general and particular solutions [24]. By using mathematical transformations, the displacement of the system is expressed as

$$x(t) = \frac{v_0}{\omega_n} \sin(\omega_n t) + \left[ x_0 - \frac{f_0}{\omega_n^2 - \omega^2} \right] \cos(\omega_n t) + \frac{f_0}{\omega_n^2 - \omega^2} \cos(\omega t)$$

(28)

$v_0$ the velocity of the system in initial conditions (m/s)
$
\omega_n$ natural angular frequency of the system (rad/s)
$\omega$ current angular frequency of the system (rad/s)
$f_0 = \frac{F_0}{m}$ (N/kg)
The maximum displacement derived from equation (28) is

\[ \frac{x_{\text{max}}}{F_0/k} = \frac{2}{1 - r^2} \]  \hspace{1cm} (29)

\[ r = \frac{\omega}{\omega_n} \] frequency ratio

From equation (29), displacement’s value depends on the frequency ratio. Figure 22 illustrates a plot of the solution equation (29) with input values \( f_0 = 1, v_0 = 0, \omega_n = \pi \text{ rad/s} \). It is clear to see that when \( 0 \leq r < 1 \), \( \frac{x_{\text{max}}}{F_0/k} \) tends to increase. When \( r = 1 \), this means that a resonance occurs and seismic frequency equals to system’s natural frequency, \( \frac{x_{\text{max}}}{F_0/k} \) becomes at peak. When \( r \gg 1 \), system displacement decreases and tends to converge to zero.

![Maximum vibration displacement plot](image)

Figure 22 Maximum vibration displacement plot

The resulting figure implies that every undamped structure has its natural frequency. If any seismic vibration has a frequency equal to the undamped structure’s natural frequency (resonance), the displacement will get its maximum value, causing the structure’s failures. This principle explains why the Tacoma bridge collapsed in history [25]. The bridge is impacted by fluid flow frequency (wind), which is called aeroelasticity and makes a resonance to the bridge’s structure.

Seismic risks can be prevented by adding a vibration isolator to the system. Another name for it but widely used in mobile vehicles is the shock absorber. It is a mechanical or hydraulic device that absorbs and dampens shock waves. Seismic energies are absorbed by shock absorbers and converted into kinematic energy and heat dissipation. The shock absorber consists of a spring
and a damper. The characteristic of a damper is the damping coefficient, denoted by \( c \). A force applied to a damper can be expressed as

\[
F_{damping} = c \cdot v
\]

\( F_{damping} \) damping force (N)
\( c \) damping coefficient (N/sm)
\( v \) velocity

The thesis assumes that crawler or mobile vehicles can be simplified as a damped system under seismic events, called base excitation. In this model, displacement is a sin function of time, and there are two displacements - displacement of the system and displacement of the seismic. Figure 23 illustrates this base excitation model.

\[
X = \sqrt{\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}}
\]

\( X \) displacement magnitude of the system
\( Y \) displacement magnitude of the seismic event
\( \zeta \) damping ratio
\( r \) frequency ratio

When designing systems, the base excitation model for a system with shock absorbers and equations (30) and (31) can be used to determine damping coefficient \( c \) and spring stiffness \( k \). By choosing appropriate values for these parameters, displacement magnitude \( X \) can be reduced as low as possible. However, since spring and damping are preload parts, stress relaxation and creep should also be considered.
3.2.8 Pressurised Water

Working in an underwater environment such as the interspace of the VV requires a system that has proper sealing. With a height of 15.637 meters, any object that dives into the interspace will face hydrostatic pressure.

Hydrostatic pressure is the pressure generated by a fluid at hydrostatic equilibrium to contact surfaces of the object under the effects of gravity. Hydrostatic pressure depends on the depth of the fluid and its density, which is expressed as follows

\[ p = p_0 + \rho gh \]  

\( p_0 \) (Pa) the pressure of zero reference point of the pressure  
\( \rho \) (\( kg/m^3 \)) the density of the fluid  
\( g \) (\( m/s^2 \)) gravitational acceleration  
\( h \) (m) depth

When an object is immersed fully or partially in the water, it receives both hydrostatic and buoyancy forces (Figure 24). This figure shows hydrostatic forces proportional to the depth surface immersed underwater, and buoyancy is the upward force against the object’s weight. The magnitude of buoyancy force follows Archimedes’ principle and equals the weight of the fluid being displaced by the object, which is given as

\[ m_{\text{displaced fluid}} = m_{\text{object in vacuum}} - m_{\text{object in fluid}} \]

![Figure 24 Model of a floating object under hydrostatic and buoyancy forces](image)

The system can dive or float by adjusting the weight and water displacement volume following Archimedes’ principle. However, the pressure becomes riskier when depth increases. The current design on ITER’s VV is 2.4Mpa for coolant water, which is a large number and requires structures to have a good material with proper thickness against this risk.
3.3 Function Risk Minimisation Model

3.3.1 Risk-Minimisation-Based Overall Function

The design goal is to develop the RM systems to operate in the In-Bioshield environment with minimum failure to ensure maximum availability of the FPP. Therefore, the RM system is conceptualised as a complex dynamic system considering maintenance operations and risk mitigation factors to minimise failure in the early design phase. Complex dynamic systems often consist of continuous physical processes integrated with discrete events.

Referring to the complex system black box in Figure 13, the black box of the In-Bioshield RM complex dynamic system is shown in Figure 25. Therefore, the black box is a risk-based function model combining the process intention (i.e., a verb of action) and the generalised variables of risk minimisation.

![In-BioShield RM System (Operation with Risk Consideration)](image)

**Legend**
- E = Main Energy
- $E_w =$ Auxiliary Energy
- $\Delta E =$ Energy Deformation
- $S =$ Input Signal
- $S_{out} =$ Output Signal
- M = Material
- $M_{deform} =$ Material Deformation
- F = Dynamic Forces
- $F_1 =$ Dynamic Forces
- $F_2 =$ Dynamic Forces
- $R_j =$ Minimised Risk
- $R_u =$ Minimised Risk

Figure 25 Black box model of In-BioShield RM system as complex dynamic system considering maintenance operations and risk variables

The input/output function variables (energy, material, information) are abstracted from the system requirements in the design driver (Table 3). The
The generalised variable is abstracted from the risk factor (Table 4) as risk effects. Finally, the risk factor and risk effect are abstracted as generalised input and output variables from Table 5.

### Table 5 Generalised Risk Variables

<table>
<thead>
<tr>
<th>Risk Minimisation Requirements</th>
<th>Risk Factor (Generalised Inputs)</th>
<th>There is a risk that</th>
<th>Risk Effect (Generalised Outputs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The system shall work properly with a maximum temperature of 100°C</td>
<td>High temperature, radiation and long-time loading or pressure</td>
<td>The In-BS RM System's components encounter creep failures</td>
<td>Creep Deformations</td>
</tr>
<tr>
<td>2. The system shall work properly with a maximum radiation level of 100Gy/hr</td>
<td>High temperature, radiation, and initial strains</td>
<td>The In-BS RM System's preload component has stress relaxation failures</td>
<td>Stress relaxation</td>
</tr>
<tr>
<td>3. The system shall be capable of working under dynamic and seismic input loads</td>
<td>High temperature and differences in the thermal expansion coefficient of materials</td>
<td>The In-BS RM System's components have thermal-stress failures</td>
<td>Thermal expansion</td>
</tr>
<tr>
<td>The system shall work properly with a maximum temperature of 100°C</td>
<td>High temperature, thermal gradient and thermal expansion coefficient of materials</td>
<td>The In-BS RM System's electrical components are getting expanded and damaged</td>
<td>Electronic failures</td>
</tr>
<tr>
<td>The system shall work properly with a maximum radiation level of 100Gy/hr</td>
<td>Radiations</td>
<td>The In-BS RM System's components have radiation damages</td>
<td>Material degradations</td>
</tr>
<tr>
<td>Radiations</td>
<td>The In-BS RM System's electrical components are getting damaged</td>
<td>Electronics failures</td>
<td></td>
</tr>
<tr>
<td>The system shall work properly with a maximum magnetic level of 0.04T</td>
<td>Magnetic Fields</td>
<td>The In-BS RM System's component is magnetised</td>
<td>Magnetised Components</td>
</tr>
<tr>
<td>Magnetic Fields</td>
<td>The In-BS RM System's electrical components get noises or disturbances</td>
<td>Electrons failures</td>
<td></td>
</tr>
<tr>
<td>The system shall operate properly in pressurised water</td>
<td>Pressurised Water</td>
<td>The In-BS RM System's components have deformations by pressure and creep under long-time loading</td>
<td>Creep Deformations</td>
</tr>
<tr>
<td>Pressurised Water</td>
<td>The In-BS RM System's electrical components are exposed to water</td>
<td>Electronics failures</td>
<td></td>
</tr>
<tr>
<td>The system shall be capable of working under dynamic/ and seismic input loads</td>
<td>Vibrations or Seismic</td>
<td>Resonance occurs (vibration frequency matches with the In-BS RM system's natural frequencies)</td>
<td>Vibration Resonance Deformation</td>
</tr>
</tbody>
</table>
3.3.2 Risk-Minimisation-Based Function Structure Modelling

A typical procedure for modelling the In-Bioshield RM complex dynamic system is to divide it into subsystems and account for their function and behaviour. Then, each subsystem is modelled and by combining the sub-system models, a complete system model is obtained.

The higher-level requirements determine the functional interrelationship representing the intended overall links between the inputs and outputs of the complex system. The input from the design drive (Table 3), risk requirements (Table 4) and risk variables from Table 5 are formulated and used as the design problem to determine solution-neutral sub-functions (Table 6).

<table>
<thead>
<tr>
<th>Overall Function</th>
<th>In-BioShield RM System (Operation with Risk Consideration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Requirements</td>
<td>The In-BioShield System shall deploy RM tools with payloads equal to or greater than 10 tons</td>
</tr>
<tr>
<td>Design Requirements</td>
<td>The Remote Maintenance System shall conduct inspection of In-BioShield components</td>
</tr>
<tr>
<td>Design Requirements</td>
<td>The Remote Maintenance System shall conduct testing of In-BioShield components</td>
</tr>
<tr>
<td>Design Requirements</td>
<td>The Remote Maintenance System shall conduct in-situ repair for In-BioShield components</td>
</tr>
</tbody>
</table>
Design Requirements

The Remote Maintenance System shall replace In-BioShield components

Risk Factor:
1. High temperature
2. Radiation
3. Long-time loading
4. Pressure

Risk Factor
1. High temperature
2. Radiation
3. Initial strains

Risk Factor
1. High temperature
2. Differences in the thermal expansion coefficient of materials

Risk Requirement
The system shall work properly with a maximum magnetic level of 0.04T
**Risk Requirement:**
The system shall be capable of working under dynamic/ and seismic input loads.

**Design Goal:**
Develop the remote maintenance systems to operate in the In-BioShield environment with minimum failure to ensure maximum availability of the FPP.

**Risk System Boundary**
Risk factor consideration for minimising risk.

---

Figure 26 presents a complete risk-minimisation-based function structure (RFSD) for the In-BioShield RM system resulting from Table 6. The figure demonstrates input energy, signal, material, and risk factor conversions to find solutions for appropriate design with minimised risk at the conceptual design.
The RFSD transfers the energy (E) to deploy the RM system, including electrical, mechanical power, compressed air or hydraulic. In addition, the "Deploy RM System" function block receives input power and operator control signals to perform maintenance tasks such as inspection, in-situ repair, and replacement. At the same time, the deployed system receives risk effects due to the input of risk factors in the overall system.

The risk factors that potentially impact the “Deploy RM System” is mitigated by three progressive mitigation functions: “Minimise Risks”, “Monitor Risks”, and the “Protect RM System” function. These functions cover and minimise all three kinds of risk defined in section 2.2.3: failure modes, situational and quality risks. After being minimised by the “Minimise Risk” function, risks will be continuously monitored to ensure that the system is still working under good conditions. The system will trigger operators and protect itself automatically if unexpected problems make these risks above predefined limits, which is demonstrated as a feedback loop from the “Protect RM System” to the “Deploy RM System” function in Figure 26.
3.3.3 Risk Minimisation Function Structure and Physical Relationship

The RM complex dynamic systems consist of continuous physical processes integrated with discrete events. Figure 26 shows the functional structure of the RM system, and the functions are fulfilled by the physical processes upon which mechanical engineering solutions are based. Selected physical effects, geometrical and material characteristics realise a physical process to ensure the function is fulfilled per the engineering task [9]. In quantitative terms, “physical effects” is described using the physical laws governing the physical quantities involved in an engineering solution. In this research, the generalised risk effects are the underlying physical quantities for the design solution for risk minimisation.

The abstraction of physical effects for risk minimisation is demonstrated in Figure 27; the inputs of this diagram are based on the expanded risk generalised variables in Figure 26 and with the physical laws derived in Section 3.2 - Background to Risk Analysis.

![Diagram](image)

**Figure 27 Abstraction of Physical Effects for Risk Minimisation**

Each block has its specific equation in this physical effect abstraction to demonstrate how risk effects are transformed into minimising risks. The output of the risk minimisation block is the sum of output parameters.

The thermal insulation block reduces temperature elevation from the In-BioShield ambient environment $T_a$. The goal is to minimise the heat flow ($Q_i$) from the In-BioShield ambient environment to the inside. During operations, the electrical component inside the system also dissipates excessive heat, which is expressed by $(1 - \eta_{elec}) \cdot P$. The active cooling aims to perform the heat exchange, reducing the total heat flows after thermal insulation and
excessive heat and minimising inside electrical devices’ temperature $t_i$ (electronics failures).

Aside from thermal factors, magnetic field risks are minimised by the magnetic shielding block. $H_1$ and $H$ are the magnetic field strength after and before the shielding layer. Similarly, using either radiation shields or radiation-hardened components helps to minimise impacts from the radiation risk factor, denoted by the input dose rate $D_0$. If using radiation shielding, the output dose rate ($D$) will be considered. Heat, magnetic field and radiation factors contribute indirectly to electronic failures.

As observed from Figure 26, the dynamic forces ($F_D$) generates both vibrations and resonance deformation risk effects. Therefore, in Figure 27, vibrations with the magnitude $A_0$ and angular velocity $\omega$ is absorbed by the shock absorbers, which work as vibration isolators for the system to prevent resonance deformations and minimise vibrations. However, thermal expansion, creep deformations ($\varepsilon^c$) and stress relaxation ($\sigma^r$) occur not only to the system’s shock absorber but also to the chassis when temperature elevates with time and must be minimised as small as possible.

Finally, the pressure resistance function block describes a physical effect caused by hydrostatic pressure on the system inside. Density $\rho$ and maximum pressure $p_0$ are inputs for the block. The maximum depth the system can resist is the output needed to maximise.

Table 7 shows the parameters for physical effect blocks listed in Figure 27. Each block has input, output variables, error, and efficiency factor $\eta_i$. Output equation $y$ is expressed as sum of each output symbol. The total efficiency of risk minimisation is defined as the product of individual efficiency factors.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Thermal Insulation</th>
<th>Excessive Heat</th>
<th>Active Cooling</th>
<th>Thermal Expansion</th>
<th>Magnetic Shielding</th>
<th>Radiation Shielding</th>
<th>Short Absorbing</th>
<th>Creep Deformation</th>
<th>Rebound Rate</th>
<th>Pressure Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_i$</td>
<td>$t_{run}$</td>
<td>$t_{rack}$</td>
<td>$t_{cool}$</td>
<td>$t_{exp}$</td>
<td>$t_{mag}$</td>
<td>$t_{rad}$</td>
<td>$t_{short}$</td>
<td>$t_{creep}$</td>
<td>$t_{reb}$</td>
<td>$t_{pres}$</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>$Q_2$</td>
<td>$Q_3$</td>
<td>$Q_4$</td>
<td>$Q_5$</td>
<td>$Q_6$</td>
<td>$Q_7$</td>
<td>$Q_8$</td>
<td>$Q_9$</td>
<td>$Q_{10}$</td>
<td>$Q_{11}$</td>
</tr>
<tr>
<td>$\xi_{thermal}$</td>
<td>$\xi_{rad}$</td>
<td>$\xi_{mag}$</td>
<td>$\xi_{short}$</td>
<td>$\xi_{creep}$</td>
<td>$\xi_{reb}$</td>
<td>$\xi_{pres}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta t_1$</td>
<td>$\Delta t_2$</td>
<td>$\Delta t_3$</td>
<td>$\Delta t_4$</td>
<td>$\Delta t_5$</td>
<td>$\Delta t_6$</td>
<td>$\Delta t_7$</td>
<td>$\Delta t_8$</td>
<td>$\Delta t_9$</td>
<td>$\Delta t_{10}$</td>
<td>$\Delta t_{11}$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\eta_1$</td>
<td>$\eta_2$</td>
<td>$\eta_3$</td>
<td>$\eta_4$</td>
<td>$\eta_5$</td>
<td>$\eta_6$</td>
<td>$\eta_7$</td>
<td>$\eta_8$</td>
<td>$\eta_9$</td>
<td>$\eta_{10}$</td>
</tr>
</tbody>
</table>

Risk Minimisation: $y = \max(\sum_{i=1}^{\text{num}}\Delta t_i, R_T, h_{\text{max}})$ + $\max(h_{\text{mag}})$

Risk Minimisation Efficiency $\eta = \prod_{i=1}^{\text{num}} \eta_i$

The output function of the physical effect abstraction for risk minimisation is demonstrated as

$$y = f(t_i, \sigma_{\text{thermal}}, H_1, D, X, \dot{\varepsilon}_c, R_T, h_{\text{max}})$$  \hspace{1cm} (34)
4 DESIGNING FOR MINIMUM RISK

This chapter introduces a study case using the function risk minimisation methodology. The hexapod (spider robot) is used as a research case.

4.1 Hexapod Study Case

Figure 28 illustrates a component diagram of the hexapod. There are five links with five independent motors on each leg of the robot: coxa, coxa, femur, tibia and tarsus joint. By controlling the motor’s angle, the hexapod’s height and position of the endpoint for each leg can be achieved.

According to Figure 28, the link \( L_{TA} \) plays a vital role in the robot since it is directly connected to the adhesion mechanism module (endpoint), provides mobility and serves as structural support for the crawler’s body. Therefore, the correct functioning of this component is of utmost importance for the reliability of the RM system. As a result, it is chosen as a hexapod component for risk minimisation.
The overall size and weight constraints should be identified to support the conceptual design. By conducting space observation for the In-BioShield area, this robot is suitable to work between the cryostat and the thermal shield. In this research, the crawler’s width and height are assumed to be 2230 mm, a height smaller than 1081 mm and weighing 80kg.

Table 8 provides the preliminary risk specification for the link $L_{TA}$, which is summarised based on the In-BioShield risk minimisation requirements (Table 4). Because the crawler is suggested to work in a dry environment (between the cryostat and the thermal shield), the pressurised water requirement (RREQ-InBS-5) can be ignored. However, additional risks such as thermal expansion, creep deformation, and stress relaxation associated with heat factor is introduced. The maximum values for preliminary risk specifications are selected based on the following explanations:

- **Electronic operating temperature**: electrical devices can operate without failures or malfunctions. The acceptable temperature range for industrial electronics products ranges from -40°C to 85°C [26]
- **Creep rate**: according to section 3.2.3, the acceptable creep rate is either 1% per 10000 or 1% per 10000 hours, depending on how frequently the machine is exposed under extreme conditions. The ambient temperature of the In-Bioshield is 100 °C. This thesis considers a critical temperature of 600°C for creep resistance and thermal expansion generated when the RM system is under long-term exposure to the ambient temperature ($T > 0.5T_{homo}$).
- **Stress relaxation**: there is no rule of thumb to determine the upper limit for stress relaxation because the drop in preloads varies depending on each material, temperature, and loading duration. As a result, the stress relaxation value with no risk minimisation is used as the benchmark for comparison. Any solution that reduces the loss of preloads in this initial value is accepted
- **Magnetic Field Level**: based on the In-BioShield environment condition
- **Radiation level**: based on the In-BioShield environment condition
- **Vibration level**: vibrations come from In-BioShield component vibrations or seismic waves. For seismic events, most seismic waves have a frequency range from 10 to 100 Hz and a displacement of up to 1 meter. However, the most severe impact does not occur when the frequency is high but when the frequency matches the system’s natural frequency (resonance or $r=1$). The transmission ratio below 1.5 during the resonance is suitable in this case.
### Table 8 Preliminary Risk Minimisation Specification for the link L<sub>TA</sub>

<table>
<thead>
<tr>
<th>Risk Factor</th>
<th>Parameter</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat</td>
<td>Operating temperature for electronics</td>
<td>50°C</td>
</tr>
<tr>
<td></td>
<td>Creep rate</td>
<td>1% per 10000 hours</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>Magnetic Field Level</td>
<td>0.04T</td>
</tr>
<tr>
<td>Radiation</td>
<td>Radiation level</td>
<td>100 Gy/hr</td>
</tr>
<tr>
<td>Vibration</td>
<td>Transmission ratio during resonance</td>
<td>1.5</td>
</tr>
</tbody>
</table>

#### 4.2 Minimum Risk Design Solution

With the abstraction of the physical effects for risk minimisation (Figure 27), working solutions were searched for various subfunctions of the study case. Thermal expansion, creep deformation, or thermal expansion physical effects have one principle. In addition, two possible working solutions can be applied to other functions, such as radiation shielding or shock absorbing.

Table 9 lists the risk minimisation solutions that can be used to design the end link L<sub>TA</sub> of the hexapod (spider robot). Thermal insulators and magnetic shields reduce risk from the In-BioShield environment to electric components inside the system. Neither radiation shields nor radiation-hardened electrical components can be considered to reduce the design's overall dimension, instead using both.

### Table 9 Design solutions for Risk Minimisation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Solution</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Insulation</td>
<td>Thermal Insulator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic Shielding</td>
<td>Magnetic Shield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation Shielding</td>
<td>Radiation Shield</td>
<td>Radiation Hardened</td>
<td></td>
</tr>
<tr>
<td>Active cooling</td>
<td>Fluid to Fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock Absorbing</td>
<td>Twin-tube Coilover</td>
<td>Monotube Coilover</td>
<td></td>
</tr>
<tr>
<td>Pressure Resistance</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since the Hexapod is a mobile robot, Coilover is more suitable to apply and has two variants – monotube or twin-tube damper, similar to available vehicles. In addition, pneumatic with internal fans can be implemented to perform heat exchange for the crawler through the umbilical cable. Finally, the risk minimisation solution for pressure resistance is not applicable in this study case because the chosen crawler work does not work underwater.
Different concepts are developed using permutations between the design solutions identified in Table 9.

4.2.1 Concept Generation

The following concept variants are based on the solutions considering design solutions in Table 9.

4.2.1.1 Concept A

Figure 29 demonstrates the first concept. The shock absorber is mounted between the electrical and adhesion modules. The adhesion module refers to the mechanical parts of the adhesion mechanism used for climbing or going over complex terrains. The electrical module is similar to an electrical cabinet, where electrical components of the adhesion module are placed and protected here.

![Diagram of Concept A](image)

Concept A's electrical module consists of four layers stacking each other, with the sequence from outside to inside: chassis, thermal insulation, and magnetic and radiation shield. The electrical components are without radiation hardened. The vibrations and seismic effects are absorbed from the shock absorber and transferred to the electrical module. At the top are umbilical
cables mounted centrally in the electrical module, bringing both main and auxiliary energy for a component inside.

4.2.1.2 Concept B

Concept B is similar to concept A but with the radiation shield excluded. Instead, radiation-hardened electrical components are utilised. In addition, concept B offers more simplifications than concept A since the radiation shields are often required to be made of unique materials (boron or lead), which could increase the size and weight of the design significantly.

![Diagram of Concept B]

Figure 30 Concept B

4.2.1.3 Concept C

In this concept, both hardened radiation components and radiation shields are used. This option offers minor impacts from radiation to the components compared to concepts A and B, but its weakness is more space and cost consumption.
4.2.1.4 Concept D

The fourth concept is slightly different in the design layout and can be found in commercial legs for disabled people. Figure 32 presents this design concept.
From the bottom, the adhesion module is connected to a shock absorber. A shock absorber is mounted at an angle from the vertical axis and connected to the electrical module through folding joints. In this design, not only does the shock absorber carry the above loads, but a part of the chassis supports it. In some worst scenarios, the chassis could perform load bearing when the shock absorber fails. However, stress can concentrate on the folding joint, which requires analysis of the bearing under high temperatures.

4.2.1.5 Concept E

Concept E inherits most features from concept D but with the radiation shield excluded. Instead, radiation-hardened components are used. The idea of concept E is similar to concept B, with a simplified redundant function to get more spaces and fewer weights.

![Concept E Diagram](image)

Figure 33 Concept E

4.2.1.6 Concept F

In concept F, radiation shields and radiation-hardened electrical components are used simultaneously. The concept’s goal is to minimise the radiation effect as much as possible.
4.2.2 Selected Concept for Further Analysis

Comparing the concepts indicates that concept B has strength in simplifying design and manufacturing. Shock absorber contacts directly with the adhesion module help to reduce seismic events and generate traction forces to keep the crawler attached to the ground surfaces. Meanwhile, concept E is slightly more complicated with a skew mounting shock absorber. Concept B removes conventional radiation shielding layers and uses radiation-hardened components to save more space and cost. This concept will be further analysed in the following sections.

4.3 Preliminary Analysis to Minimise Risk

It is critical to analyse and define the rough calculations and layout of the chosen concept. The preliminary analysis comprised the following:

- Determining materials for the identified concept, including structural chassis and fasteners
- Calculating characteristic values for identified risk minimisation components (Table 10)
- Determining dimensions and layout for each identified component, based on the design for fault-free and self-help principles
### Table 10 Risk minimisation function carriers

<table>
<thead>
<tr>
<th>Functions</th>
<th>Function carriers</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Insulation</td>
<td>Thermal Insulator</td>
<td>Insulator thickness $t_{\text{insu}}$</td>
</tr>
<tr>
<td>Magnetic Shielding</td>
<td>Magnetic Shield</td>
<td>Shield thickness $t$</td>
</tr>
<tr>
<td>Active Cooling</td>
<td>Fluid to Fluid</td>
<td>The energy required for cooling $Q_{\text{exchange}}$</td>
</tr>
<tr>
<td>Shock Absorbing</td>
<td>Shock Absorber</td>
<td>Damping coefficient $c$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spring coefficient $k$</td>
</tr>
<tr>
<td>Creep and Relaxation</td>
<td>Chassis</td>
<td>Maximum stress allowed $\sigma$</td>
</tr>
<tr>
<td>Thermal Expansion</td>
<td>Spring</td>
<td>Relaxation coefficient $\tau$</td>
</tr>
<tr>
<td></td>
<td>Fasteners</td>
<td>Layout for thermal expansion, creep and stress relaxation</td>
</tr>
</tbody>
</table>

#### 4.3.1 Structure Consideration

The robot's chassis is its body frame. It plays a crucial part in the design by supporting the body, providing protection, forming shapes, and adding to the overall weight of the robot. In the risk minimisation context, a good design body chassis helps to minimise the deformations caused by the dynamic forces and creep phenomenon without consuming too much space, weight and material cost.

First, structural chassis and materials needed to be considered. In order to increase the rigidity of the structure, the space frame structure is chosen for the chassis body. Space frame design offers well lightweight and interior support needed. It is widely used in architecture and structural engineerings, such as chassis design for aircraft, cars or motorcycles.

The chassis design aims to minimise the mass without failure under design loads. Materials and shape (cross-section) are free variables and affect the structure. Figure 35 shows a free-body diagram of the link LTA chassis. It can be seen that each element in the space frame chassis can be considered as beams carrying maximum load $P$.

![Figure 35 Freebody diagram of chassis](image-url)
Different cross-section shapes are considered for chassis elements. Due to minimising the cost and weight of the structure, a tabular shape is preferred. Cutting and welding can quickly fabricate and assemble these two sections in the chassis. Shape-efficient factors from [11] can be used to choose an appropriate leg chassis. Both material and shape affect the structural performance. However, in this case, only one material is used for the chassis so that the shape factor can be considered separately.

Figure 36 illustrates the shape factor formulas for bending strength between rectangular and circular tubes [11].

Consider a thickness $t = 1\, \text{mm}$ between a circle ($d = 2r = 5\, \text{mm}$) and rectangular tubes ($b = h = 5\, \text{mm}, t = 1\, \text{mm}$). By substituting to the equation, the shape bending factor for rectangular is

$$
\phi_B^f = \frac{1}{\sqrt{2}} \sqrt{\frac{h}{t} \left(1 + \frac{3b}{h}\right)^{3/2}}
$$

Bending factor for circular tube

$$
\phi_B^f = \frac{3}{\sqrt{2\pi}} \sqrt{\frac{2.5}{1}} = 1.89
$$

The result from equations (35) and (36) shows that under the same material, a rectangular tube ($b = h = 5\, \text{mm}, t = 1\, \text{mm}$) has a better bending performance than a circular one ($d= 5\, \text{mm}, t = 1\, \text{mm}$). Therefore, the rectangular tube is preferred.

4.3.2 Material Consideration

Three appropriate materials for nuclear power plants with their parameters are listed in Table 11. These are high-temperature alloys with higher creep resistance than other materials [19]. The material’s characteristics are taken
from the GRANTA EDUPACK (level 3) database, a material library to support material education.

Table 11 Material consideration for chassis

<table>
<thead>
<tr>
<th>Material</th>
<th>SS 316 L(N)</th>
<th>SS 304 L(N)</th>
<th>Inconel 625</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>8000</td>
<td>7900–7910</td>
<td>8400–8480</td>
</tr>
<tr>
<td>Young Modulus (GPa) @ 650°C</td>
<td>144</td>
<td>142</td>
<td>167</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>280–300</td>
<td>270–290</td>
<td>365–434</td>
</tr>
<tr>
<td>Min-Max Service Temp (°C)</td>
<td>-250–925</td>
<td>-250–925</td>
<td>-273–982</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>14.4–15.6</td>
<td>14.4–15.6</td>
<td>9.9–10.7</td>
</tr>
<tr>
<td>Ferromagnetism</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Price (USD/kg)</td>
<td>3.75–4.82</td>
<td>3.06–3.9</td>
<td>31.8–39.2</td>
</tr>
<tr>
<td>Metal Fabrication</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
</tr>
</tbody>
</table>

Table 11 shows that Inconel 625 has the highest strength but is also the heaviest and densest material compared to austenitic stainless steel 316L(N). The 316L(N) has the second high-strength properties after Inconel 625 with a fair price. On the other hand, stainless steel 304L(N) does not have good properties like the remaining two materials but has the lowest price. Fabrication (machining, forming, and welding) in 316L(N) and 304L(N) is pretty good.

The thesis chose stainless steel 316L(N) as a safe choice for chassis and fasteners due to its balance of fabrication, cost, and strength. In addition, this material is commonly used for nuclear components and is not impacted by the magnetic field. Its specific properties for further analysis and simulation are demonstrated in Table 12.

Table 12 AISI Stainless Steel 316L(N) input properties for analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>8000</td>
</tr>
<tr>
<td>Young modulus @ 600°C</td>
<td>GPa</td>
<td>148</td>
</tr>
<tr>
<td>Thermal conductivity @ 600°C</td>
<td>W/mK</td>
<td>23.4</td>
</tr>
<tr>
<td>Thermal expansion coefficient@ 600°C</td>
<td>10⁻⁶°C⁻¹</td>
<td>18.3</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>N/A</td>
<td>0.28</td>
</tr>
<tr>
<td>Tensile Yield Strength</td>
<td>MPa</td>
<td>580</td>
</tr>
<tr>
<td>Compressive Yield Strength</td>
<td>MPa</td>
<td>280</td>
</tr>
</tbody>
</table>

4.3.3 Fastener Consideration

The link LTA works, and the end link of a leg for climbing application mainly works under tensile loads. Due to high holding strength, the bolt connection is chosen as a fastener between the electrical module and the shock absorber.
There are four bolts to join the two parts. Bolt size can be calculated based on EN 1993-1-8 standard [27], as follows
\[
F_{t,Rd} = \frac{0.9 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}
\]  
(37)

- \(F_{t,Rd}\): design tension resistance per bolt
- \(f_{ub}\): ultimate tensile strength
- \(\gamma_{M2}\): partial safety factor for resistance of bolts
- \(A_s\): tensile stress area of a bolt

Based on the positions of bolts in the link LTA, it can be seen that these bolts are mostly under tensile forces during climbing operations. The maximum tensile force for each bolt in worst case scenario is equal to the mass of the hexapod (80kg) dividing the total number of bolt connection \( F_{t,Rd} = \frac{80}{4} = 196.2N \). Since a magnetic field and high temperature exists in the In-Bi-OShield area, a bolt grade 8.8 (\(f_{ub} = 800MPa\)) is compatible due to its high strength and can tolerate the degradation of materials caused by radiation. Substituting back to the equation (37), the minimum tensile stress area of about is
\[
A_s = \frac{196.2 \cdot 1.25}{0.9 \cdot 800} = 0.34mm^2
\]  
(38)

The fastener size selection for the concept must have a tensile stress area greater than 0.34 based on equation (38).

4.3.4 Magnetic Field Solution

From the B-H curve, with \(B = 0.12T = 1200\) Gauss, the permeability of mumetal 80% nickel alloy can be around 240000. It is sufficient to use a standard Mumetal annealed sheet with a thickness of 0.5mm [28]. Its mechanical properties can be seen in Table 13.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition</td>
<td>80% Ni, 5% Mo, 0.3-0.5% Mn, 0.1-0.4%Si, Fe Balance</td>
</tr>
<tr>
<td>Density kg/m$^3$</td>
<td>(8.7 \cdot 10^{-3})</td>
</tr>
<tr>
<td>Curie temperature °C</td>
<td>420</td>
</tr>
<tr>
<td>Thermal expansion coefficient (10^{-6}°C^{-1})</td>
<td>12</td>
</tr>
<tr>
<td>Thermal conductivity W/mK</td>
<td>19</td>
</tr>
<tr>
<td>Specific heat (J \times kg^{-1} \times K^{-1})</td>
<td>420</td>
</tr>
<tr>
<td>Melting temperature °C</td>
<td>1450</td>
</tr>
<tr>
<td>Yield strength MPa</td>
<td>280</td>
</tr>
<tr>
<td>Tensile strength MPa</td>
<td>650</td>
</tr>
</tbody>
</table>
4.3.5 Vibration Solution

Equation (29) from section 3.2.7 is called the transmission ratio (TR). The damping constant and spring coefficient can be chosen from the transmissibility curve with different damping ratio lines [24]. A transmissibility curve plotted from equation (29) with different damping ratios can be seen in Figure 37.

From the curve, it can be seen that when resonance occurs \( r = 1 \), the transmissibility ratio mostly depends on the damping ratio. The more damping coefficient, the more displacement and force are reduced during the resonance. However, too high damping ratios could lead the TR to become prominent when \( r \gg 1 \).

With identified TR at resonance, a vertical axis \( x=1 \) is plotted to see available values of \( r \) and \( \zeta \) for design (Figure 37). Based on this figure, a shock absorber with a damping ratio greater than one is appropriate for the system. It means that

\[
\zeta \geq 1 \leftrightarrow c > 2\sqrt{km} \tag{39}
\]

Shock absorber selection in the concept design should satisfy the equation’s constraint (39).
4.3.6 Thermal Transfer Solution

Materials with low thermal conductivity are appropriate for thermal insulation layers. At the beginning of the thesis, Multi-Layer Insulation (MLI) blanket - the thermal insulation with very low thermal conductivity ($10^{-5}$ W/mK) used widely in spacecraft was considered due to its superior insulation properties [29]. However, it applies only to prevent radiation heat transfer types (outer space vacuum environment), which must be positioned on the product’s outer surfaces. This increases the risks of cleanliness, where tiny residual scratches resulting from the robot’s movements could fall into the reactor. As a result, typical industry candidates are compared instead. These materials can be placed between the robot’s outer covers and internal components to minimise conduction heat transfer. Table 14 lists these materials with their properties from the thermal insulation handbook [30] and datasheet of existing industrial products [31] [32].

Table 14 Material consideration for Thermal Insulation

<table>
<thead>
<tr>
<th>Material</th>
<th>Density kg/m$^3$</th>
<th>Thermal Conductivity W/mK</th>
<th>Max service temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microporous Min-K TE 1400</td>
<td>320</td>
<td>0.029–0.031</td>
<td>982</td>
</tr>
<tr>
<td>Rock mineral wool</td>
<td>60-160</td>
<td>0.033–0.064</td>
<td>900</td>
</tr>
<tr>
<td>Calcium silicate</td>
<td>220-265</td>
<td>0.054–0.082</td>
<td>1000</td>
</tr>
<tr>
<td>Ceramic fibre (blanket)</td>
<td>64-192</td>
<td>0.03–0.07</td>
<td>1250</td>
</tr>
</tbody>
</table>

The microporous material contains tiny pores with a diameter of less than 2nm. It has advantages in several applications, including thermal insulation in aerospace and fire doors for the elevator. Rock mineral wool is used in marine, offshore and heavy industries. Applications for calcium silicate can be found in the petrochemical, general, and energy sectors. Finally, ceramic fibre is frequently employed in commercial buildings’ electrical systems and fire prevention.

In order to choose the appropriate one, MATLAB was used to plot equation (2) to see the effect of insulation thickness in various insulation materials under a temperature of 100°C, using minimum thermal conductivity values from Table 14. The insulation area is based on the design with $A = 0.02064m^2$. The output is illustrated in Figure 38.

From Figure 38, it is clear that a significant difference can be seen in microporous material. When the thermal insulation layer becomes thicker, its heat rate converges to values between 0-100W. Based on the graph and dimension of the concept design, the appropriate design-cut-off point is 10mm.
with microporous material. This thickness value is enough performance without consuming too much space in the design.

![Figure 38](image_url)

**Figure 38 Effect between insulation thickness and insulation materials**

600°C is a critical temperature for incidents. During regular operation, active cooling can be considered equal to or below 100°C. The excessive heat is assumed to be around $Q_e = 8W$. Using chosen thickness, the heat rate after the insulation layer is $Q_i = 3W$. The total heat received by the system is

$$Q_{receive} = Q_i + Q_e = 11W$$  \hspace{1cm} \text{(40)}$$

The preliminary analysis assumes that there would be a steady flow condition during cooling operation; with a constant heat capacity ($C_p$) under atmospheric pressure, the air is an ideal gas. Changes in kinetic and potential energy are insignificant. The active cooling must neutralise the net heat rate received to minimise the risk. The energy required for cooling is

$$Q_{exchanger} = Q_{receive} = 11W$$  \hspace{1cm} \text{(41)}$$

The result from equation (41) is the input for the concept design of the active cooling system.

**4.3.7 Thermal Expansion Solution**

From the concept layout, it can be observed that thermal stress can exist on connection joints in fasteners. The risks become significant if fastener materials differ from chassis (AISI 316L(N)). Clearances shall be added to prevent thermal stresses on two different materials. By using the thermal expansion
equation (13) with $\bar{\alpha}$, which is an average thermal expansion coefficient between 22 and 600°C. Thermal expansion is derived as

$$L = L_0 e^{\bar{\alpha}(T-T_0)} = L_0 e^{1.74 \cdot 10^{-5}(600-22)} \approx 1.01L_0$$  \(42\)

Equation (42) shows that clearance in joint connections should be approximately 1% of the total length. Thermal stress exists in both radial and axial directions. While axial stress is related to stress relaxation, the maximum radial thermal stress at 600°C can be approximated by

$$\sigma_{\text{thermal}} = E\Delta L = 148 \cdot 10^9 \cdot (e^{1.74 \cdot 10^{-5}(600-22)} - 1) = 1496 \text{ MPa}$$  \(43\)

An alternative besides adding clearances is to use thermal-stress-free fasteners developed and used by NASA to mitigate thermal stress risks [18], [33]. Figure 39 demonstrates this fastener type’s principle if used for the link LTA. The thermal-stress-free boundary is chosen with $p = \frac{\alpha_y - \alpha_2}{\alpha_x - \alpha_2} = 1$, which means that the thermal expansion coefficient ratio in the x and y direction between the fastener and chassis part is the same. The cone geometry of the boundary can be derived as

$$y = Ax^p = Ax$$  \(44\)

Constant A depends on the bolt diameter, and initial position $z_0$. Customed thermal stress-free fasteners can be created using the geometry function from equation (44). This fastener performs better and is proven to work under 1000°C [33]; however, it requires both flanges to have precise conic holes, which is difficult to fabricate. Thus, using unique fasteners instead of standard ones increase the cost significantly. As a result, conventional fasteners with dimensions tolerated for thermal expansion are used to minimise the cost.
4.3.8 Creep and Relaxation Solution

According to preliminary specifications in Table 8, the designing part is expected to have a deformation limit of 1% creep in 10000 hours. This value is the steady-state creep rate, which can be converted as

\[ 1\% \text{ creep in } 10000 \text{ hrs } \rightarrow \dot{\varepsilon} = 10^{-6} \text{hr}^{-1} = 2.78 \times 10^{-10} \text{s}^{-1} \]  

(45)

The thesis uses creep raw data for AISI Stainless Steel 316L(N) from experimental results [34] to approximate and simulate the creep phenomenon in the design. Based on it, a steady-state creep rate vs stress is plotted with regression for each temperature line, which is demonstrated in Figure 40.

Figure 40 Steady-state creep rate plot with regressions

The homologous at 550 °C temperature \( T_{\text{ homo}} = \frac{823}{1723} = 0.477 \), less than 0.5, explains why the R-squared value is relatively low, with 0.7118 in Figure 40. Regression lines with high fitting values (600, 650, 700 and 750 °C) are used to calculate stress values for 1% creep at 10 000 and 100 000 hours, as shown in Table 15.

<table>
<thead>
<tr>
<th>Time</th>
<th>600</th>
<th>650</th>
<th>700</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 000 hours</td>
<td>142.69 MPa</td>
<td>68.75 MPa</td>
<td>38.16 MPa</td>
<td>12.86 MPa</td>
</tr>
<tr>
<td>100 000 hours</td>
<td>98.2 MPa</td>
<td>24.96 MPa</td>
<td>3.34 MPa</td>
<td>N/A</td>
</tr>
</tbody>
</table>
With the stress of 142.69MPa at 600 °C for 10 000 hours, the creep rupture graph from [35] predicts the structure's lifetime if continuously loaded under this stress. The result shows that the structure might fail in $2 \times 10^5$ hours, which is relatively safe compared with 10000 hours.

In practice, the designing part should work below this 140MPa stress margin. Using a safety factor of 3, the working stress allowed under this condition can be estimated as

$$\sigma_{working} = \frac{142.69}{3} = 47.56 \text{ MPa}$$  \hspace{1cm} (46)

The result from equation (46) is used for concept designs. Designing parts shall be optimised to avoid stress concentration exceeding 47.56 MPa.

Creep simulation can be performed by Finite Element Analysis (FEA) software using the Norton-Bailey model. However, it is required to have constant parameters beforehand. These constants can be derived by solving four variable equations from Table 15.

Recall the Norton-Bailey creep formula from equation (16). Because the creep simulation is performed at a maximum temperature of 600 °C so that, the model can be simplified as temperature independence ($C_3 = 0$). The equation is expressed as follows

$$\dot{\varepsilon}^c = \frac{C_1 \sigma}{C_1 > 0} e^{\frac{C_2}{T}}$$  \hspace{1cm} (47)

By substituting creep rate and stress values in Table 15 (under 600 °C), the final creep constants are derived as

$$\begin{align*}
2.78 \times 10^{-10} &= C_1 (142.69 \times 10^6)^{C_2} \\
2.78 \times 10^{-11} &= C_1 (98.2 \times 10^6)^{C_2}
\end{align*}$$  \hspace{1cm} (48)

$$\begin{align*}
C_1 &= 1.568 \cdot 10^{-60} \\
C_2 &= 6.162 \\
C_3 &= 0
\end{align*}$$

Aside from creep, stress relaxation in designing parts exists on both the fastener and spring (in the vibration isolator). Stress relaxation depends on the stiffness of preload parts, so materials with lower young modulus are preferred for fasteners. However, due to the magnetic field and cleanliness constraints, non-ferrous materials with slightly lower strength than AISI 316L(N), such as AISI 316H, are considered for the design.
Empirical stress relaxation data for stainless steel AISI 316H can be referred to from [36], [37]. The stress relaxation curves for 316H stainless showed that from a temperature greater than 500°C, high preload stress relaxes more significantly than those lower. Increasing bolt quantities in the flange connection can reduce the minimum initial preload stress and is considered a solution for fastener relaxation risk. For instance, six or eight bolts shall be used instead of four. If eight bolts were used, the tensile force for each bolt is 

\[ F_{t,Rd} = \frac{100 - 9.81}{8} = 122.625N, \]

which is equivalent to 46% initial stress reduction.

For a long-term solution, fasteners and springs' lifetime can be estimated to replace these parts after a specific operation time. The estimation requires empirical data are collected for the In-BioShield area, which includes:

- Creep and stress relaxation data for 316H fastener under magnetic and radiation environment
- Creep and stress relaxation data for spring under both magnetic and radiation environment

The constant coefficients for simulation (maxwell model) of stainless steel 316H can be approximated using empirical data [37]. Under 600°C, with a 1.925% fixed strain

\[ \sigma = \sigma_0 e^{-\frac{\xi}{\tau}} = \sigma_0 e^{-\frac{E_t}{\eta}} \]

\[ \leftrightarrow 52.7 = 220 e^{-\frac{34661}{\tau}} \rightarrow \tau = 24213.23 \]

4.3.9 Dynamic Loads Solution - Design for Self-help

Vibrations (seismic) or dynamic loads in the In-BioShield area are associated forces that cause changes in friction and drop preloads significantly. Since fasteners rely on friction for tensioning, it is easily impacted and loosened by vibrations.

Standard commercial locking washers are used for dynamic load conditions. Nord-Lock and Wedge-Locking are popular suppliers for this locking washer type. The principle for these locking washers is demonstrated in Figure 41, which is already patent registered and uses a self-balancing solution.
Self-balancing solutions enhance the total effect by offsetting the initial effect with a supplemental effect obtained from an associated force [9]. The mechanism consists of two wedge-lock washers with radial teeth on one side and cams on the other. Because the cam angle $\alpha$ is greater than the thread pitch angle $\beta$, therefore during vibrations, the upper washer tends to move first and get blocked by the cam, preventing the bolt/nut from rotating. Here, vibrations are associated forces, and the cam locking effect is the supplemental effect. The associated forces act opposite the main forces, and the self-balancing solution is implemented.

The design of link $L_{TA}$ suggested using a NordLock washer to secure fastener connections from vibration. Figure 42 shows the use of Nord lock washers in the 3D layout.
4.4 3D Model of the Concept Solution

The exploded view of the risk-minimised and optimised link $L_{TA}$ concept solution for the In-BioShield environment is shown in Figure 43.

First, the shock absorber is assembled into the body chassis by bolt fasteners. Then thermal insulation with magnetic shielding is inserted into the body frame. Finally, thin cover panels are assembled with screw connections to prevent external damage to the thermal insulation block or microporous material scratches from falling outside the In-BioShield area. All fasteners are used with Nord-lock washers to minimise self-loosening effects by vibrations.

![Exploded view of the optimised link L_{TA}](image)

Figure 43 Exploded view of the optimised link $L_{TA}$

Figure 44 gives a cross-section view of the link $L_{TA}$ (left) and the inside thermal insulation with a shielding structure. A 0.5mm Mu-Metal is coated inside the thermal insulation to protect the internal electrical component from external magnetic fields. All structure is positioned and fixed inside the chassis by a HI-Grade Stainless Steel hook and pile fastener [38], a fastener that fastens two lineal trips by hooks and loops.
Cover panels and threaded holes are designed with tolerances for thermal expansion, as shown in Figure 45. These panels have a 1% maximum length reduction, so thermal stress risk does not occur when the temperature reaches 600°C.
5 SIMULATION FOR MINIMUM RISK

In order to evaluate risk minimisation performance, the thesis uses MATLAB Simulink to simulate link LTA under an assumed environment, as shown in Figure 46. The simulation program is based on the risk minimisation physical effect in Figure 27. There are five risk blocks: thermal transfer, expansion, creep, relaxation deformation and vibration. In addition, a PID controller is added to the Thermal Transfer block to simulate the active cooling feature, keeping internal hardware cooled at 50°C when the temperature is equal to or below 100°C.

![Simulink diagram](image)

Figure 46 Simulink diagram

Inputs for simulation are illustrated in Figure 47. These are time-series data with a range of 10 hours of maintenance. Inputs represent three stages. From the beginning to the first two hours, the temperature is relatively low (80°C), then it increases to a maximum working condition (100°C) from 3 to 6 hours. Finally, the temperature ramps to a critical condition (600°C) at 8 hours.

The input graph pattern is similar to dynamic stress and vibration frequency. The dynamic stress for the working condition is 47.56 Mpa and 143Mpa for critical conditions. For seismic, the input is the frequency ratio representing how much the vibration exceeds the system’s natural frequency. The critical frequency ratio is 1, which is a resonance event.
The excessive heat input is a random gaussian noise that expresses variations caused by a component inside the system. It has a standard deviation of about 0.01 with an average value of 8W.

Based on these inputs, the simulation derives the temperature, stress deformations and relaxation after 8 hours of working. Dividing the outputs by the inputs approximates how much risks are reduced. One exception is vibration isolation, which eliminates system fracture during resonance instead of minimising it. By taking the average value, the percentage of risk can be shown in Figure 48.
From Figure 48, it can be seen that at the beginning of the simulation ($0 \leq t < 0.1 \cdot 10^4 s$), the risk tend to drop significantly due to the enabling of active cooling, which begins to cool down the internal temperature. Then, the risks are stabilised at around 48% in working conditions. When the temperature exceeds 200°C, the risk increases spikily because the active cooling block is disabled. In critical conditions, only the vibration isolator and stress relaxation contribute to the risk reduction and make the overall risk percentage around 88%. The detailed simulation results are explained in the following sections.

### 5.1 Heat

Figure 49 demonstrates the internal temperature for electrical components (left) and the heat flow that active cooling provides. The internal temperature is kept constantly around 50°C by the PID controller when temperatures are below 100°C; otherwise, the system is shut down automatically and awaits rescuing operations. The active cooling heat flow shows that during the working condition (100°C), 9.5W of heat flow is needed to cool down internal parts, which is close as calculated in the preliminary analysis (section 4.3.6). Variations in the gaussian noise can explain the differences between the preliminary calculation (11W) and the simulation (about 9.5W).

![Internal Temperature and Active Cooling Heat Flow](image)

The thermal expansion simulation for the chassis (SS 316 L(N)) during temperature elevation is given in Figure 50, which is based on equation (13). It can be seen that when the temperature reaches 100°C, structures expand around 0.1% in length and get a maximum of 1.1% when 600°C.
5.2 Vibrations

The effectiveness of the vibration isolator is illustrated in Figure 51. The graph is based on the transmission ratio. The actual damping coefficient in the detail design might differ due to many factors, but in this simulation, the damping coefficient is chosen as $\zeta = 3$.

Figure 51 Vibration Isolation between the damper and undamped system

Figure 51 shows a contrast between with and without damper. Because the chosen damping coefficient is large in normal vibration, the maximum...
displacement is equivalent to 0.7-0.9 vibration displacement. However, when resonance occurs, it damps the system displacement and prevents failure ($t \geq 28800s$). While in undamped system, the maximum displacement is infinity due to zero division.

### 5.3 Creep and Relaxation

The creep and stress relaxation simulation assume that the component is continuously loaded under 600°C temperature for eight hours and with 1.925% initial fixed strain. This differs slightly from the thermal and seismic simulation, which depends on the temperature time-series input.

Figure 52 illustrates the creep and relaxation simulation in risk equivalent measure. Dynamic stresses are then converted to an equivalent steady-state creep rate in the next 10000 hours. Figure 52 (left) shows that the equivalent creep rate is relatively low under normal working conditions. The risk percentage of creep is derived by dividing the current steady-state creep rate by a maximum 1% creep rate, which is an assumption for the critical creep rate.

![Figure 52](image)

*Figure 52 Current creep rate in 10k hours (left) and stress relaxation (right)*

Six-bolt connection is chosen instead of eight because the more fastener quantity in a circular hole, the closer the distance between them. If the distance between two holes becomes too narrow, it could lead to potential thermal fatigue failures. Figure 52 (right) shows that the stress relaxation risk is significantly reduced in the first six hours with six bolts and converges when the loading time exceeds eight hours.
6 DISCUSSION

In this work, a new design methodology for risk minimisation is developed based on the Risk-based-minimisation Function Structure (RFSD) and abstraction of physical effect.

Potential risks are considered at the beginning of the conceptual design, and the risk minimisation requirements (RMR) are derived from the initial high-level requirements. It serves as the foundation for the abstraction of risk factors and effects as generalised variables for the system function structure.

The RFSD has the advantage of revealing interfaces between risk variables, giving designers an overview of how different risk factors correlate and lead to new potential risks in the early design stages. Visualising them under function structure simplifies risk analysis and makes it easier to trace or identify risk consequences to the product’s functions. In addition, it could help to identify new risks without depending too much on historical data.

Aside from the RFSD, the abstraction of the physical effect for risk minimisation provides designers with a more comprehensive and logical understanding of how risks could be mitigated. Solution principles can be found to reduce these risks and accomplish the design goal corresponding to this physical effect abstraction. However, this approach requires designers to conduct a detailed literature review of risks relevant to the design context beforehand, focusing deeply on the physics laws behind them.

For the hexapod study case, a preliminary analysis and simulation model was built based on the RFSD and abstraction of physical effect. Risk minimisation performance is represented under a percentage indicator under a time domain, estimating how much risks could be minimised, as shown in Figure 48. This is done by taking mathematical transformations of the risk’s output parameter before and after solution implementation. The simulation model has the advantage of verifying the preliminary analysis and assessing the performance of selected risk minimisation solutions when the detailed design of the product is not yet formed.

The results from the simulation indicate that the concept obtained from the new design methodology satisfies the defined requirements to work under extreme environments. In practice, prototypes with further empirical experiments should be developed along with other stages of engineering design, such as embodiment or detailed design, to verify and optimise solutions.
7 CONCLUSIONS

In this research, a new design methodology for risk minimisation in early design stages was developed and verified through a design study case. Minimising risk is important for systems working inside the In-BioShield area of the DEMO fusion power plant, increasing the availability. The design research process was separated into four major stages according to the DRM methodological approach: research clarification, descriptive study I, prescriptive study, and descriptive study II. It helps to break down a complex design problem into systematic and progressive steps, improving design practices and the research.

The methodology starts with deriving risk minimisation requirements from design requirements during identifying problem spaces. Based on it, risk factors and effects are constructed under generalised variables.

An overall function is generated based on this result. Subsequently, the detailed RFSD is built to see the interrelationships between risk factors and their effects on the product. Generating physical effects for risk minimisation is essential to find appropriate working solutions that minimise identified risks aside from working solutions that fulfil the main product's function. As a result, the risk minimisation concepts are shaped and selected for the simulation to estimate how well the risk could be minimised.

The simulation model confirms the effectiveness of risk minimisation solutions for the design study case. Solutions such as thermal insulation, magnetic shield, shock absorber, adding clearances and special fasteners with appropriate material selections give the product the ability to resist and work in a harsh environment with approximately 52% (working condition) and 12% (critical condition) of risk reduction. This simulation model is constructed based on the abstraction of physical effects for risk minimisation.

Three functions such as “Minimise Risks”, “Monitor Risks”, and “Protect RM System”, are mentioned in the RFSD diagram (Figure 27) of the design study case to mitigate all three kinds of risks – failure modes, situational and quality risk. In this thesis, the study focuses only on the “Minimise Risks” function block to minimise failure modes. The remaining two functions are recommended for future research, including:

- The decomposition and solution developments are based on the “Monitoring Risks” function block in the RFSD to monitor and detect potential risks during the system’s operation. The work might include the design of hardware and algorithms
• The decomposition and solution developments are based on the “Protect RM system” function block in the RFSD to mitigate situational and quality risks during the system’s operation. The work might include the design of hardware and algorithms.
• The study of these three functions works under a single system to minimise all three kinds of risk and their efficiency.
• A design methodology is built upon the design methodology in this work to improve the construction of these three functions fully under a single RFSD to mitigate all risks.
8 REFERENCES


9 APPENDIX A: 2D DRAWINGS
10 APPENDIX B: CREEP DATA

The creep raw data used in this thesis are extracted from the experimental results of the study [34] under section 7.2. The test is based on the M5 x 30 mm specimen.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Stress</th>
<th>Creep rate %</th>
<th>Creep rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>380</td>
<td>660</td>
<td>0.00066</td>
</tr>
<tr>
<td>550</td>
<td>360</td>
<td>20</td>
<td>0.00002</td>
</tr>
<tr>
<td>550</td>
<td>340</td>
<td>51</td>
<td>0.000051</td>
</tr>
<tr>
<td>550</td>
<td>320</td>
<td>159</td>
<td>0.000159</td>
</tr>
<tr>
<td>550</td>
<td>300</td>
<td>3.2</td>
<td>0.000032</td>
</tr>
<tr>
<td>550</td>
<td>260</td>
<td>3.9</td>
<td>0.000039</td>
</tr>
<tr>
<td>550</td>
<td>240</td>
<td>1</td>
<td>0.000001</td>
</tr>
<tr>
<td>600</td>
<td>300</td>
<td>1749</td>
<td>0.001749</td>
</tr>
<tr>
<td>600</td>
<td>280</td>
<td>1525</td>
<td>0.001525</td>
</tr>
<tr>
<td>600</td>
<td>260</td>
<td>733</td>
<td>0.000733</td>
</tr>
<tr>
<td>600</td>
<td>240</td>
<td>150</td>
<td>0.00015</td>
</tr>
<tr>
<td>600</td>
<td>220</td>
<td>48</td>
<td>0.000048</td>
</tr>
<tr>
<td>600</td>
<td>200</td>
<td>19</td>
<td>0.000019</td>
</tr>
<tr>
<td>600</td>
<td>180</td>
<td>9.3</td>
<td>0.000093</td>
</tr>
<tr>
<td>600</td>
<td>150</td>
<td>1.2</td>
<td>0.000012</td>
</tr>
<tr>
<td>650</td>
<td>240</td>
<td>5333</td>
<td>0.005333</td>
</tr>
<tr>
<td>650</td>
<td>200</td>
<td>1240</td>
<td>0.00124</td>
</tr>
<tr>
<td>650</td>
<td>160</td>
<td>157</td>
<td>0.000157</td>
</tr>
<tr>
<td>650</td>
<td>140</td>
<td>60</td>
<td>0.00006</td>
</tr>
<tr>
<td>650</td>
<td>120</td>
<td>13.5</td>
<td>0.000135</td>
</tr>
<tr>
<td>650</td>
<td>100</td>
<td>3.8</td>
<td>0.000038</td>
</tr>
<tr>
<td>700</td>
<td>170</td>
<td>3680</td>
<td>0.00368</td>
</tr>
<tr>
<td>700</td>
<td>150</td>
<td>1653</td>
<td>0.001653</td>
</tr>
<tr>
<td>700</td>
<td>120</td>
<td>293</td>
<td>0.000293</td>
</tr>
<tr>
<td>700</td>
<td>100</td>
<td>102</td>
<td>0.000102</td>
</tr>
<tr>
<td>700</td>
<td>80</td>
<td>19</td>
<td>0.000019</td>
</tr>
<tr>
<td>700</td>
<td>60</td>
<td>2.6</td>
<td>0.000026</td>
</tr>
<tr>
<td>750</td>
<td>100</td>
<td>1760</td>
<td>0.00176</td>
</tr>
<tr>
<td>750</td>
<td>80</td>
<td>318</td>
<td>0.000318</td>
</tr>
<tr>
<td>750</td>
<td>60</td>
<td>60</td>
<td>0.00006</td>
</tr>
<tr>
<td>750</td>
<td>40</td>
<td>10</td>
<td>0.00001</td>
</tr>
</tbody>
</table>
APPENDIX C: SIMULATION CODES

11.1 Thermal Insulation

clear all
clc

thickness = linspace(0.0001, 0.1, 10000);
tempi = 50;  % internal temperature
k1 = 0.029;  % thermal conductivity of microporous
k2 = 0.064;  % thermal conductivity of rock mineral wool
k3 = 0.074;  % thermal conductivity of calcium silicate
k4 = 0.079;  % thermal conductivity of ceramic fiber
A = 0.02064;  % area of insulation layer
% t = 24*60*60;  % service hour in second
Q1 = double.empty;
Q2 = double.empty;
Q3 = double.empty;
Q4 = double.empty;
for i=1:length(thickness)
    Q1(i) = k1*A*(tempi-tempi)/thickness(i);
    Q2(i) = k2*A*(tempi-tempi)/thickness(i);
    Q3(i) = k3*A*(tempi-tempi)/thickness(i);
    Q4(i) = k4*A*(tempi-tempi)/thickness(i);
end
thicknessmm = thickness*1000;
plot(thicknessmm, Q1)
hold on
plot(thicknessmm, Q2)
plot(thicknessmm, Q3)
plot(thicknessmm, Q4)
xline(10)
ylim([0 1000]);
xlim([0 30]);
grid on;
title('Effect of insulation thickness in various insulation materials');
legend('Microporous k=' +k1, 'Rock mineral wool k=' +k2, 'Calcium silicate k=' +k3, 
'Ceramic fiber k=' +k4, 'Cut-off point');
xlabel('Insulation Thickness [mm]')
ylabel('Heat Receive [W]')
11.2 Vibration Isolator

clear all
clc

r = linspace(0, 10, 1000);

d1 = 0.08;
d2 = 0.1;
d3 = 0.4;
d4 = 1;
d5 = 3;

TR1 = double.empty; % Damping ratio 1
TR2 = double.empty; % Damping ratio 2
TR3 = double.empty; % Damping ratio 3
TR4 = double.empty; % Damping ratio 4
TR5 = double.empty; % Damping ratio 5

for i=1:length(r)
    TR1(i) = sqrt(1+(2*d1*r(i))^2)/sqrt((1-r(i)^2)^2+(2*d1*r(i))^2);
    TR2(i) = sqrt(1+(2*d2*r(i))^2)/sqrt((1-r(i)^2)^2+(2*d2*r(i))^2);
    TR3(i) = sqrt(1+(2*d3*r(i))^2)/sqrt((1-r(i)^2)^2+(2*d3*r(i))^2);
    TR4(i) = sqrt(1+(2*d4*r(i))^2)/sqrt((1-r(i)^2)^2+(2*d4*r(i))^2);
    TR5(i) = sqrt(1+(2*d5*r(i))^2)/sqrt((1-r(i)^2)^2+(2*d5*r(i))^2);
end

plot(r,TR1)
hold on
plot(r,TR2)
plot(r,TR3)
plot(r,TR4)
plot(r,TR5)
xline(1)
grid on;
title('Transmissibility curve');
legend('ζ=', '+d1', '+d2', '+d3', '+d4', '+d5', 'Resonance');
xlabel('Frequency Ratio r')
ylabel('T.R.')
%ylim([0 0.1]);
%xlim([0 2]);
11.3 Risk Minimisation Evaluation

11.3.1 Simulink Diagrams

Figure 53 Main simulation diagram

Figure 54 Creep-Deformation sub-block
Figure 55 Stress-Relaxation sub-block

Figure 56 Thermal expansion sub-block

Figure 57 Thermal stress sub-block
Figure 58 Thermal-Transfer sub-block

Figure 59 Conditional sub-block 1

Figure 60 Conditional sub-block 2
11.3.2 Visualisation Codes

```matlab
%Plot Internal Temperature
figure
subplot(1,2,1)
plot(out.internaltemp_withoutcool)
hold on
plot(out.internaltemp_withcool)
hold on
grid on;
title('Internal Temperature');
xlabel('Seconds [sec]');
ylabel('Temperature [°C]')
legend('Without Active Cooling','With Active Cooling');
xlim([0 36000]);
ylim([0 620]);
text(10800,80, '\uparrow Working Condition')
text(28800,600, '\uparrow Critical Condition')

%Plot Active Cooling Heat Flow
subplot(1,2,2)
plot(out.heatflow)
hold on
grid on;
title('Active Cooling Heat Flow');
xlabel('Seconds [sec]');
ylabel('Heat Flow [W]')
xlim([0 21600]);

%Plot Creep Rate
figure
subplot(1,2,1)
plot(out.creeprate)
hold on
grid on;
title('Current Creep Rate in 10,000 hours');
xlabel('Seconds [sec]')
```
ylabel('Current steady-state creep rate [%]')
ylim([0 1.5]);
xlim([0 36000]);
subplot(1,2,2)
%Plot Stress Relaxation
plot(out.relaxed_stress)
hold on
plot(out.relaxed_stress4)
grid on;
title('Stress Relaxation');
xlabel('Seconds [sec]')
ylabel('Relaxation [MPa]')
legend('Relaxation in 6 bolts', 'Relaxation in 4 bolts');
xlim([0 36000]);

%Plot Thermal Expansion
figure
plot(out.expansion)
hold on
grid on;
title('Maximum Thermal Expansion');
xlabel('Seconds [sec]')
ylabel('% Length Expanded')
xlim([0 36000]);

%Plot seismic output
figure
plot(out.TR)
hold on
plot(out.withoutdamper)
grid on;
title('Vibration Isolation Performance');
xlabel('Seconds [sec]')
ylabel('System Displacement/ Environment Displacement')
xlim([0 36000]);
ylim([0 1.5]);
legend('With Damper', 'Without Damper');

%Plot Simulation Input
figure
subplot(2,2,1)
plot(out.inputtemp)
title('In-BioShield Temperature')
grid on;
xlabel('Seconds [sec]')
ylabel('oC')
xlim([0 36000]);
ylim([0 700]);
text(10800,100,'\uparrow Working Condition')
text(28800,600,'\uparrow Critical Condition')
hold on
subplot(2,2,2)
plot(out.excessiveheat)
grid on;
title('Excessive Heat')
xlabel('Seconds [sec]')
ylabel('Heat Flow [W]')
xlim([0 21600]);
ylim([5 10]);
subplot(2,2,3)
plot(out.inputstress)
title('Dynamic Stress')
grid on;
xlabel('Seconds [sec]')
ylabel('Stress [MPa]')
text(10800,47.6,'\uparrow Working Condition')
text(28800,142.69,'\uparrow Critical Condition')
xlim([0 36000]);
subplot(2,2,4)
plot(out.inputseismic)
title('Input Frequency Ratio')
xlabel('Seconds [sec]')
ylabel('r')
xlim([0 36000]);
ylim([0 6]);
text(28800,1,'\uparrow Critical Condition')
grid on;
sgridtitle('Simulation Input');

%Plot Risk Minimisation Output
figure
plot(out.y)
hold on
grid on;
title('Risk Graph')
text(10800,48,'Working Condition')
text(28800,87,'Critical Condition')
xlabel('Seconds [sec]')
ylabel('% Risk')
xlim([0 36000]);
ylim([0 100]);