# Analyzing Human Errors Responsible for a Pressure Vessel Failure

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## Abstract

In the era of technological advancement it is still critical to analyze human errors that are responsible for failures of pressure vessels. This is because the adoption of latest technologies cannot totally or abruptly displace the role played by human in design, fabrication and maintenance of equipment including pressure vessels. Thus, this paper adopted a case study research methodology aimed at examining human errors and their causal factors responsible for pressure vessel failure. The analysis feedback established that the slip error in original design contributed to the pressure vessel leak. Furthermore, the design error served as a latent error in the fabrication, inspection and maintenance process until the leak developed in the longitudinal weld of the shell. The lapse error and mistake due to the inadequacy of the repair or replacement procedure resulted in the partial re-fabrication of the shell with its original design error. This discussed the causal factors responsible for the identified human errors and then made recommendations to enhance design and repair or replacement processes so as to minimize human errors. This paper makes contribution by providing insights on pressure vessel failure analysis in viewpoint of human errors and their causal factors.

## Keywords
Failure, Human Error, Pressure Vessel Design, Replacement

## 1. Introduction

Pressure vessels are used in various industries such as petrochemical, power generation, chemical processing, pulp and paper and many more for storage of different fluids in different phases. Designs and repairs of pressure vessels are governed by legislations and health and safety standards. So those who design and repair pressure vessels should also ensure that they comply with the requirements of applicable standards and regulations.
"Shell, head, attachments, and piping are some of the components that commonly fail" in a pressure vessel (TRC Engineering, 2004). Human beings play a major role during the design, fabrication, operation and maintenance of systems or equipment. Now, human interactions with the systems or equipment varies according to the phase, but they are subject to deterioration due to human error (Dhillon, 2014). In the paper by NOPSEMA (2015), human error is viewed as "a failure of a planned action to achieve a desired outcome". The design, fabrication, inspection and maintenance of pressure vessels are highly reliant of human activities. Dhillon and Liu (2006) classified human errors according to the phases under which they occur. Their classification included operating errors, assembly errors, design errors, inspection errors, installation errors and maintenance errors. Thus, human reliability is key to the success of pressure vessel life-cycle so as to minimize failures related with human error. There are various causes that give rise to human error. In Reason (1990) and Alkhaldi et al. (2017) human error is classified as follows:

- Slip error – sometimes referred to as procedural error which means not performing the activity as desired or planned.
- Lapse error – means that the action was missed.
- Mistake – means the insufficiency of the plan to accomplish the desired outcome.

Both a good plan of activity but performance of an unintended action as well as poor plan of activity but performance of an intended action lead to an undesired outcome or human error. "Past experiences indicate that during the equipment design phase often errors are made that adversely affect equipment maintainability and, directly or indirectly, the occurrence of maintenance errors" (Dhillon, 2014). These design errors can be seen as latent errors during fabrication, operation and maintenance of an equipment. Poor repairs as part of maintenance errors have a significant influence on various equipment breakdowns which accordingly can give rise to risks associated with failures of equipment and personal accidents (Mason, 2007 cited in Dhillon, 2014). "Errors are seen as consequences rather than causes, having their origins not so much in the perversity of human nature as in "upstream" systemic factors" (Reason, 2000). This means that human errors can be viewed as symptoms of weaker organizational systems and processes. The literature review study by Nkosi et al. (2020), revealed a number of human factors responsible for human error such as work design/planning/layout, poorly written procedures, manuals and work instructions, time pressures, culture, routine or repetitive work and others. Pressure vessels as technical systems do not only suffer from technical errors but also from human errors. Majid et al. (2015) cited in Wyckaert et al. (2017) confirm this by indicating that "nevertheless, technical problems are not the only factors leading to the susceptibility rupture of pressure vessels". According to TRC Engineering (2004) some common types of pressure vessel failures are cracking, leakage, faulty design, faulty inspection, improper fabrication practice, welding problems and discontinuities. It is further stated that design errors, fabrication errors, and substandard maintenance form part of the causes of pressure vessel failures. There are many other causes reported in their paper but in this study those that are more related with human were extracted. The study by Dong and Chi (2000) cited in Luo and Zhang (2013) revealed that, lack of design and technical force in pipeline design and thermal calculations led to design defects as a consequence boiler pressure parts could not operate for a long term or have stable operation. Therefore, this led the danger to the plant to be hidden as a latent error. On the other hand the weld crack, undercut and porosity have potential risks that caused weld leakage squib (Li and Yang, 1988 cited in Luo and Zhang, 2013). The study by De Marcellis-Warin et al. (2006) cited in Wyckaert et al. (2017) revealed that major risks such as, explosion, leaks, emission of toxic products and more that are related with storage of dangerous material stem from human errors. Depending on the nature of fluid contained in the pressure vessel, leaks and cracks can lead to explosion, environmental pollution, plant shutdowns and damage and devastating injury of personnel.

Every system, equipment, or component failure happens for a reason and the causes of failures can be attributable to design and inadequacy of procedures (TRC Engineering, 2004). So, design related errors can be fixed through redesign and procedural errors will require the enhancement of a procedure to prevent future occurrences. According to Deac et al. (2010), prevention of accidental failures include measures such as:

- Compliance with basic maintenance conditions
- Compliance with operational conditions
- Discovering and preventing failures
- Standardizing repair methods, and
- Preventing human errors

Now, through the adoption of proper failure analysis, the root cause or causes contributing to pressure vessel failure can be identified leading to the development of corrective and preventive measures.

The aim of this study is to analyze human errors responsible for the leakage and crack of a pressure vessel and their causal factors. Furthermore, to make recommendations that may enhance the pressure vessel design and repair or replacement processes.

## 2. Research Methodology

### 2.1. Case Study Research Methodology

Most of the information related with the empirical world has been discovered through the use of case study research and innumerable esteemed classics in each field of research are case studies (Flyvbjerg 2011). According to Starman (2013), case studies form a major portion of research methodologies that have been used in social sciences and have emerged as beneficial specifically in practice-oriented disciplines. Based on this, one can deduce that the use of a case study research is key when the aim is to generate knowledge or insights that will influence the practical world. In this study a case study research approach was used. The aim was to unearth the causes of pressure vessel failure that are associated with human error which is normally ignored or overlooked and more focus is given to technical causes such as corrosion, fatigue and many more.

Even though there is long history and an extensive use of case study methodology but it has not received much attention compared to other methodologies and in some instances researchers mistake it for other methodologies of research (Starman, 2013). Thus, it was necessary for the researcher in this study to deeply understand the case study research methodology so as to appropriately guide this research study.

Sturman (1997) defines a case study as "a general term for the exploration of an individual, group or phenomenon".

In this study the case study research was adopted as an exhaustive description of a single case and its evaluation through the classification of an event along with description of the discovery process (Mesec 1998 cited in Starman, 2013). Furthermore, the case study intends to describe and analyze the event with an aim of unearthing constituents or variables, patterns (theoretical purpose), and performance of activities in advancement (practical purpose) (Starman, 2013). In this study the theories associated with pressure vessel failure, human error, repair and replacement were evaluated. Then, the practical knowledge or insights were established. The case study research also aims to deduce crucial themes and findings that may assist in forecasting future trends, elucidating issues that have been hidden earlier so as to apply in practice, and/or providing insights for explicitly comprehending a critical research problem (USC Libraries, 2020). The adoption of case study methodology in this study was for both to discover the previously hidden issues so as to enhance practical application and to provide insights for understanding the origins of human error in pressure vessel failure something that is normally overlooked or poorly done in pressure vessel failure investigation. Now since this study used a case study research to collect data associated with the past event, it is classified as a retrospective case study (Thomas, 2011). The analysis is done to evaluate the past event with an aim of developing preventive measures or making recommendations that can assist in preventing future events.

This study followed a descriptive case study research, which according to Yin (1993) cited in Starman (2013) it needs a theory to facilitate the gathering of data and the theory should be clearly indicated prior the study and be examined for adequacy and relevance. Various scholarly writings were identified and reviewed to identify the key theories and concepts that could help in understanding the pressure vessel failure in the viewpoint of human error. Relying predominantly on the use of pre-existing theories to explain the case is classified as disciplined-configurative study (Eckstein, 1975 cited in Willis, 2014). The aim of the study was to close the application research gap, since there are various human error studies and models that have been used to address issues of equipment failure in aviation and marine, yet there is limited use in pressure vessel industry. Illustrative descriptive study was used with aim of providing the readers with the concepts or themes together with the common language for comprehending the topic.

Like any other method, case study research comes with criticisms. The main criticism of the case study research is that, the case selection is subjective or there is selection bias which is associated with the researcher having previous insight about the case. This can cause the researcher to choose a case because he has partiality toward a specific hypothesis (George and Bennett 2005). But, this can also serve as a strength since the previous knowledge of the researcher can assist in developing a research framework of higher quality. In this study the researcher was involved as a design verification engineer who identified the design error that was responsible for pressure vessel failure. In case study research since the event is examined in its natural or practical context, various data gathering method such as interviews, document reviews, archival records, and direct and participant observations are used (Yin, 2009). Given the nature of this study document reviews, discussions and design calculations were adopted for data collection and analysis. It was concluded that case study research was the relevant approach for this particular study. Table 1 presents the suggestions for conducting a credible case study as suggested by (Sturman, 1997 cited in Starman 2013). The researcher summarized the activities conducted in line with these suggestions.

Table 1. The suggestions and actions taken to ensure the credibility of a case study

| Suggestion | Action |
|---|---|
| Explain the data gathering techniques | The following procedures were discussed and used in this study:<br>• Document analysis<br>• Design calculations<br>• Discussions |
| Present the data gathered in a manner that is organized for analysis or reanalysis | Results obtained through document analysis, design calculations and discussions are presented in results and analysis section. |
| Report the negative circumstances | The access to the plant was limited to the user and inspectors, thus some critical information that was not on the documents was obtained through telephonic discussions and photos. |
| Recognize the potential biases | The researcher had prior knowledge of the case study as stated in this section. However, this helped in determining an adequate theoretical framework to guide the study. |
| Record the fieldwork evaluation | The field work was stated in this section which involved the identification of the leaks which was done by the user and the review of documents which was done by the researcher. The discussions as well were conducted as stated in this section. |
| Distinguish between assertion and evidence | The researcher ensured that the information that was deduced and obtained through evidence were clearly distinguished. |
| Distinguish between the primary and secondary data | • Primary Data: Document analysis, discussions and design calculations related with the case.<br>• Secondary data: Review of books, journals, conferences and industry reports related with pressure vessel failure, human error, and repair or replacement. |
| Reports and diaries should be used to trace various activities involved in the research. | The detailed design reviews, calculations, and incident reports are kept by the user and approved inspection authority. Where applicable minutes of the meeting were recorded. |
| Ensure the reliability of data collected | The data obtained from approved documents and discussions with engineers who are directly linked to the repair and replacement project. The deep understanding of design and operation of pressure vessels enabled the researcher to work on the data that was deemed credible. |

It should be noted the research problem of this study could have been researched by using surveys or interviews within the pressure vessel industry to evaluate the practices and patterns failure analysis and the knowledge of human factors engineering associated with analysis of human errors. However, these could have limitations in giving rigor that the case study research gives especially in incident investigations with an aim of developing corrective and preventive measures and deducing practical recommendations. The case study was chosen for its ability to rigorously establish deep insights and focus in establishing the influences of the occurrence of events. The next subsection briefly present the case of a pressure vessel failure.

## 2.2. Pressure Vessel Failure

The air receiver which is classified as a pressure vessel for an evaporator plant within the petrochemical industry presented small leaks during the hydrostatic pressure testing. The vessel was subjected to magnetic particle testing to confirm the leaks and to properly identify the areas in which they have occurred. The cracks had occurred on the longitudinal weld of the shell close to the dished end or head. The areas under which the small cracks occurred on the vessel are illustrated in Figure 1 below.

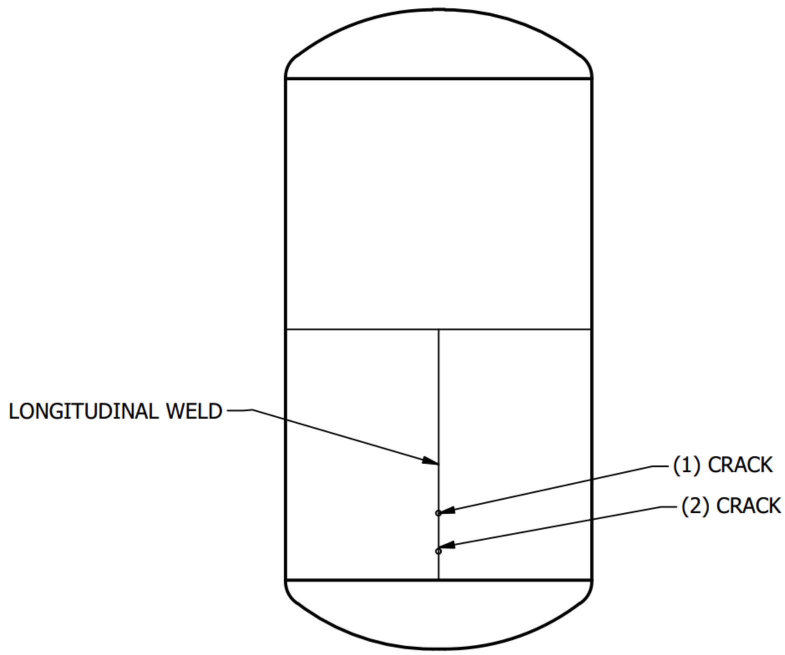


Figure 1. Presentation of crack location/s on the pressure vessel

The user of the vessel began a process of replacing the vessel by following repair and replacement procedures. Their findings was that the vessel failed due to poor weld. They then sent the replacement design documents (calculations and drawings) of the air receiver based on the original design, for verification by an approved inspection authority (AIA) to check for compliance. The use of the original documents was based on the legislative philosophy that in repairs or replacement, original documents can be used if the issue was not related with design. The design verification process conformed that the original design documents were approved by relevant signatories and authorities. However, based on the experience of the design verification engineer in pressure vessel design, repairs and human error philosophy it was noticed that, it was unusual for this type of a pressure vessel to fail or present leaks in a period of less than 10 years. The design verification engineer proposed the extension of the design verification scope which is normally adopted for repairs or replacement documents when there are no design related issues. The scope had to include performance of independent set of calculations to rule out the possibilities of design errors. The fabrication drawings were also reviewed to see if they correlated with calculations. The evaluation of the adequacy of design was based on ASME VIII Div 1 which was the design code used in the air receiver design. The following formula was used to determine the shell thicknesses of the pressure vessel:

$$t = \frac{P\,R}{(SE+0.4P)} \tag{1}$$

Where,

t = Shell required thickness
P = Operating pressure

R = Shell outside radius
S = Allowable stress
E = Joint efficiency

The data that was used with this formula for determining the thicknesses of the shell of the air receiver are presented in Table 2 below.

Table 2. Design parameters used in the air receiver calculations

| | |
|---|---|
| Design code: | ASME VIII Div 1 |
| Design pressure: | 1350 kPa |
| Design Temperature: | 60 °C |
| Operating Pressure: | 1350 kPa |
| Operating Temperature: | 40 °C |
| Material: | Carbon Steel, SA 516 Gr 70 |
| Allowable Stress: | 138 MPa |
| Shell Outer Diameter: | 1222 mm |
| Shell Thickness: | 6 mm |

The following section presents and discuss the results of this research study.

## 3. Results

### 3.1. Results and Discussions

This section presents at the same discusses the results obtained from the case study of a pressure vessel failure.

The study discovered that the pressure vessel leaks were not due to technical failure (weld defects) alone as alluded by the user. However, there was a design error which served as latent error in the fabrication, inspection, operation, and maintenance as well as replacement process. This was picked up by the researcher who thoroughly investigated the original calculations and drawings to identify possible errors. It was found that instead of using a 0.85 joint efficiency in the shell thickness equation as stated in the calculation summary and fabrication drawing, a joint efficiency of 1 was used. This mistake made the designer to wrongly recommend a thinner thickness instead of a thicker one as presented in Table 3 below.

Table 3: Thickness results

| Joint Efficiency | Thickness | Radiography |
|---|---|---|
| 1 (100%) | 5.56 mm | Full |
| 0.85 (85%) | 7.00 mm | Spot |

Now, based on the results it is clear that the air receiver was supposed to be fabricated using a 7 mm thickness as opposed to 6 mm thickness. Therefore, since the thickness of 6 mm was used for fabrication, the vessel was supposed to be subjected to full radiography for proper identification of weld deformities instead of doing spot radiography. Through document review and discussions this error was attributable to the following reasons:

- The use of manual calculations without proper verification of input data
- Poor design review process of the manufacturer to identify errors or to ensure compliance and quality of the design
- The time pressure to complete other projects

- Weakness in the verification process conducted by the design verification engineer of the inspection authority who should have used independent set of calculations to verify the compliance of the manufacturer's calculations and drawings.

This design error affected the manufacturing, inspection, operation and maintenance process since it was hidden as a latent error waiting for the day to emerge as an active failure.

The error that could have led to the air receiver to leak again after replacement was related with human error in the replacement process. The manufacturer attended the issue of weld defects but did not consider the possibilities of human error in the failure investigation. Okoh and Haugen (2014) cited in Sheikhalishahi, et al. (2016) reviewed accident investigations and reports and 69% of these reports showed planning and fault detection as the most frequent causes of failure (latent and active). The researcher who delved into the analysis of human errors to assist in elimination of design error. The manufacturer or user missed out the design error during their analysis as results of the following:

- Poor awareness or lack of focus on human errors in investigation of pressure vessel failure.
- Weak failure investigation procedures that overlook the possibilities and impact of human error.
- Time pressure to return the air receiver to operation.
- Inadequate repair procedures
- Culture of using original documents as is for repair or replacement if design issues are ruled out.

This failure was prevented through the use of independent calculations that picked up the design error embedded in the original design. The materials had already been bought and re-fabrication process had partially started using the thinner shell thickness of 6 mm which was based on full radiography. The advice was to transfer 100% radiography to both the design report summary and manufacturing drawings. This would mean that instead of spot radiography they would do full radiography on welds to identify all unacceptable deformities or those that are not within acceptable limits.

Table 4 below presents the summary of findings of the failure analysis process with the main focus on human error related causes and error classification. The human error classifications discussed by Reason (1990) and Alkhaldi et al. (2017) were used to classify the outcome of action as shown in outcome column of Table 4.

Table 4. Human error analysis of a pressure vessel

| Activity | Plan | Action | Outcome | Description |
|---|---|---|---|---|
| **Original Design** | Adequate | Unintended | Slip error | The intent was to use 85% joint efficiency. Thus, it was stated on the calculation summary and indicated on the manufacturing drawings. However, the actual calculation was based on 100% joint efficiency. |
| **Fabrication** | Inadequate | Intended | Mistake | Design error served as a latent error. Hence, the fabrication was appropriate but for a wrong design. This means that spot radiography was used on welds whereas full radiography should have been used. |
| **Statutory Inspection** | Inadequate | Intended | Mistake | Design error was carried over to inspection. So, the inspection was sufficient on a wrong fabrication. |
| **Repair / replacement process** | Inadequate | Intended | Lapse error and Mistake | Due to regulations and common practice in repairs and replacement, the original documents were used for re-fabrication. The only thing that was identified as the cause of the crack is the poor quality of weld. The original design report and drawings were sent to an approved inspection authority to verify if they have been previously approved by relevant parties as per legislation. |

The results of the study are in line with the conclusion reached by Myszewski (2012), which indicated that human errors are ineffectiveness of organizations. This is also supported by Rothblum (2000) who concluded that "most human errors tend to occur as a result of technologies, work environments, and organizational factors which do not sufficiently consider the abilities and limitations of the people who must interact with them, thus "setting up" the human operator for failure".

### 3.2. Recommendations

Based on the results and discussions presented above, the following recommendations were made:

- The failure investigations should focus on both technical causes of failure and human error equally.
- Human error should not be viewed as a cause of failure but rather as a weakness of a process, system and organization.
- Human error should present a company with an opportunity to improve organizational processes rather only retraining and disciplining or punishing those that commit errors.
- Manufacturers should review and improve their design review processes
- Checklists should be used to ensure critical steps in design, maintenance and repairs of pressure vessels are adhered to.
- There should be awareness training on human errors for manufacturers or designers of pressure equipment.
- There should be proper job design and planning to minimize the impact of time pressure
- Calculations sheets or software packages should be validated for accurate analysis and results.

To try prevent repair / replacement issues from reoccurring or to enable the repair process to properly identify the root cause of failure, the basic process is proposed in Figure 2 below.

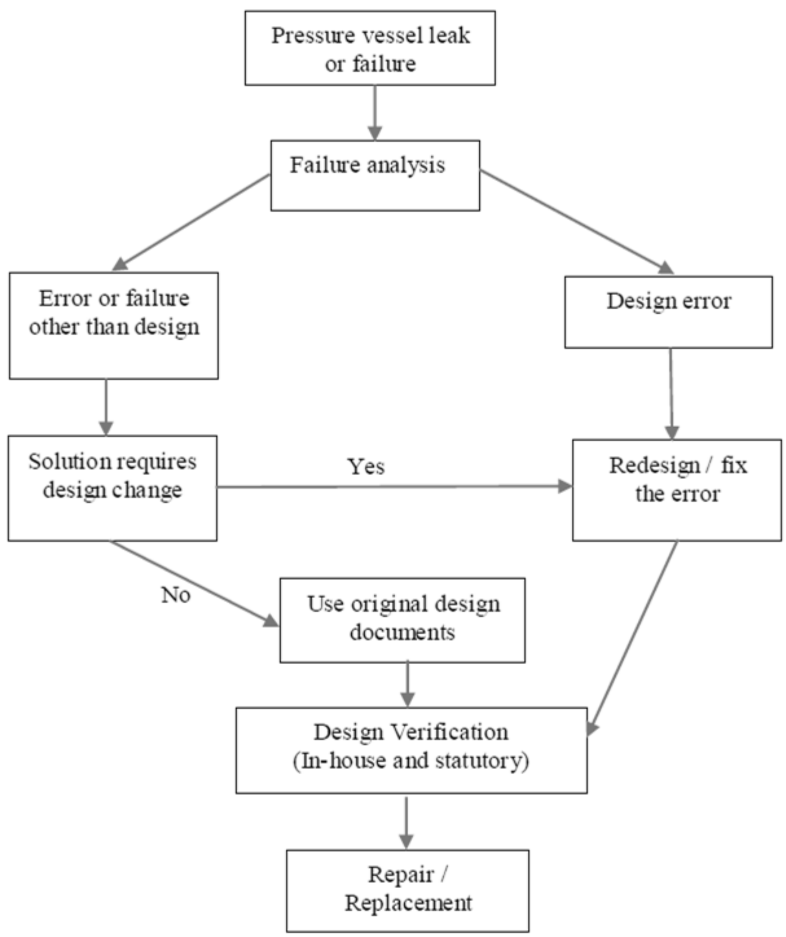


Figure 2. The proposed basic pressure vessel repair / replacement process after failure

It should be noted that this basic repair / replacement process should be followed together with best practices in failure and root cause analysis. The design verification process should always use independent set of calculations to ensure that the critical features of a pressure vessel are complaint.

## Conclusions

The aim of this paper was to unearth human errors responsible for cracks and leak of a pressure vessel and their causal factors. Design error was discovered to be the main contributor to the pressure vessel failure which then served as a latent failure in the fabrication, operation and maintenance process. This study presented and discussed various causes of the design error. The vessel could have also failed after repairs since the user did not incorporate human error analysis in the failure diagnosis process. Thus, the user began to refabricate the vessel using the original design documents that were found to contain an error. This paper discusses the causes of the manufacturer to miss out the design error and recommendations that were made. The paper makes the following conclusions:

- The designers of pressure vessels should establish robust or enhance design review practices so as to minimize design errors. This is because the design review process of the manufacturer was found to be not well developed to assist in the identification of design errors especially when there are time and economic pressures.
- Users of pressure vessels should be able to do basic pressure vessel calculations to verify if the pressure vessels that they have purchased are adequately designed or not. This would have helped to identify the design error in the original design phase.
- The repair or replacement process should include proper failure analysis or root cause analysis so to identity and eliminate the original cause/s of failure.

It should be noted that the legislation and health and safety standards are not manuals but they give minimum requirements to ensure safe design, fabrication, use and maintenance of pressure vessels. Thus, the engineers are still responsible for good engineering judgement to ensure proper analysis of design results and the adoption of adequate repair and replacement practices. Future work can be extended by including a number of case studies and even using quantitative methods to further unearth the contribution of human errors in failures of pressure vessels.

This study makes contribution in the human factors engineering domain and pressure vessel design, and replacement by providing insights on human errors responsible for pressure vessel failure and their causal factors. This study can be used by designers, manufacturers and users of pressure vessel to minimize failures associated with human error. It can also be used by researchers as part of the agenda to address human errors in pressure vessel design, fabrication, operation and maintenance.

## Acknowledgment

- This work is supported by DHET University Capacity Development Grant (UCDG) 2020, University of Johannesburg, South Africa.

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## Biography

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