Spring 2018

Case Study on the Development of Engineering Design Modification Projects for U.S. Nuclear Power Plants: A Knowledge Retention Tool in Support of the Longevity and Resilience of the Nuclear Power Industry

Pamela M. Torres-Jiménez
Old Dominion University

Recommended Citation

Torres-Jiménez, Pamela M.. "Case Study on the Development of Engineering Design Modification Projects for U.S. Nuclear Power Plants: A Knowledge Retention Tool in Support of the Longevity and Resilience of the Nuclear Power Industry" (2018). Doctor of Engineering (D Eng), dissertation, Engineering Management, Old Dominion University, DOI: 10.25777/7af3-1382
https://digitalcommons.odu.edu/emse_etds/26

CASE STUDY ON THE DEVELOPMENT OF ENGINEERING DESIGN MODIFICATION PROJECTS FOR U.S. NUCLEAR POWER PLANTS: A KNOWLEDGE RETENTION TOOL IN SUPPORT OF THE LONGEVITY AND RESILIENCE OF THE NUCLEAR POWER INDUSTRY

by

Pamela M. Torres-Jiménez
B.S. December 2006, University of Puerto Rico at Mayagüez
M.S. December 2010, Virginia Commonwealth University

A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF ENGINEERING

ENGINEERING MANAGEMENT AND SYSTEMS ENGINEERING

OLD DOMINION UNIVERSITY
May 2018

Approved by:

Adrian V. Gheorghe (Director)

Resit Unal (Member)

Charles B. Daniels (Member)

James H. Warren, Jr. (Member)

Ionut Purica (Member)

ABSTRACT

CASE STUDY ON THE DEVELOPMENT OF ENGINEERING DESIGN MODIFICATION PROJECTS FOR U.S. NUCLEAR POWER PLANTS: A KNOWLEDGE RETENTION TOOL IN SUPPORT OF THE LONGEVITY AND RESILIENCE OF THE NUCLEAR POWER INDUSTRY

Pamela M. Torres-Jiménez
Old Dominion University, 2018
Director: Dr. Adrian V. Gheorghe

The nuclear power industry in the United States (U.S.) has gone through various changes throughout its history. Most recently, plans to grow the industry through the construction of new power plants have ceased. Because of this, the industry is at a period where the longevity and resilience of existing nuclear power plants are vital to its subsistence.

One of the ways existing nuclear power plants can assure longevity and resilience is by performing engineering design modifications efficiently and at a lower cost. Strategic plans, such as the Delivering the Nuclear Promise, can support nuclear utilities to achieve this. Another strategy to accomplish longevity and resilience is to ensure individuals performing these projects possess the proper knowledge to complete tasks efficiently while being cost-effective. Knowledge retention is the main purpose of this research project.

This doctoral dissertation develops a case study for engineering design modification projects at nuclear power plants, with the intention of it becoming a knowledge retention tool to support the longevity and resilience of the industry. A literature review of subjects such as an overview of nuclear power plants, license renewal, resilience, and knowledge management comprises the first part of this paper. The literature review is followed by the description of the research methodology and the results of the research. Three parts comprise the results section. Part one develops a work breakdown structure (WBS) for a design modification project. Part two

provides a list of activity descriptions that need to be completed as part of a conceptual design package, including estimated person-hours and proposed durations for each activity. The third part performs a risk assessment using the Failure Modes and Effects (FMEA) tool. This section identifies potential failure modes for each activity, causes of failure, human performance tools that can help prevent or detect the failures, and recommends actions to address and mitigate the risks identified. The results of this case study demonstrate how, with the correct knowledge, engineering design modification risks can be mitigated and activities can be accounted for when developing project estimates. This information can assist the future development of efficient and cost-effective projects within the nuclear industry.

This doctoral dissertation is dedicated to a special person who, without knowing it, has given me utmost inspiration to work hard every single day and become a better version of myself; to my daughter, Alexa M. Graham. Even though you are still young, I hope that in the future you can see this project as an example of hard work and sacrifice. Hopefully, it will become your inspiration to work hard for what you want and to never give up on your dreams. Success will not come easy, but rest assured that I will be next to you every step of the way to guide and support you. That is the greatest gift I could ever give to you.

ACKNOWLEDGEMENTS

First of all, I would like to thank my mother, Iris P. Jiménez Guadalupe, for being the prime example of hard work and sacrifice, and always being there for me and my brother Michael L. Navedo Jiménez. Without her help and encouragement, I would have never made it as far as I am today. To my daughter, Alexa M. Graham, my fiancé, Rodney D. Graham, and my grandmother, Iris Guadalupe Concepción, thank you for your undeniable support throughout this journey.

I will also like to extend many thanks to my advisor, Dr. Adrian Gheorghe, for believing in me and helping me through this research. Thanks also go to my committee for dedicating their time and guidance through this effort. To my colleagues, thank you for your support and for providing a helping hand when needed.

NOMENCLATURE

ACI	American Concrete Institute
AD	Applicability Determination
AE	Architectural Engineering
AMP	Aging Management Program
AMR	Aging Management Review
AOV	Air Operated Valve
ASME	American Society of Mechanical Engineers
AWS	American Welding Society
BWR	Boiling Water Reactor
CAD	Computer Aided Design
CCA	Cause and Consequences Analysis
CFR	Code of Federal Regulations
CLB	Current Licensing Basis
DAR	Design Attribute Review
EDF	Électricité de France
EQ	Environmental Qualification
FLEX	Diverse and Flexible Coping Strategies
FMEA	Failure Modes and Effect Analysis
FSAR	Final Safety Analysis Report
FTA	Fault Tree Analysis
FWT	Filtered Water Tank

GALL	Generic Aging Lessons Learned
HAZOP	Hazard and Operability Analysis
HRA	Human Reliability Analysis
HU	Human Performance
I&C	Instrumentation and Controls
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
INPO	Institute of Nuclear Power Operations
IPA	Integrated Plant Assessment
JSA	Job Safety Analysis
KPI	Key Performance Indicator
LER	License Event Reports
MOV	Motor Operated Valve
MUPRA	Multi-Unit Probabilistic Risk Assessment
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Association
NNS	Non-Nuclear Safety Related
NPP	Nuclear Power Plant
ODU	Old Dominion University
OE	Operating Experience
P&ID	Process and Instrumentation Drawing
PDF	Portable Document Format
PHA	Preliminary Hazard Analysis

PI	Performance Improvement
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RPN	Risk Priority Number
SAR	Safety Analysis Report
SDP	Standard Design Process
SDPSC	Standard Design Process Steering Committee
SFP	Spent Fuel Pool
SME	Subject Matter Expert
SSC	System, Structure, or Component
TMI	Three Mile Island
TVO	Teollisuunden Voina
U.S.	United States
U.S. NRC or NRC	United States Nuclear Regulatory Commission
WBS	Work Breakdown Structure

TABLE OF CONTENTS

Page

LIST OF TABLES xv

LIST OF FIGURES xviii

Chapter

1. INTRODUCTION 1
  1.1. Problem Background 2
  1.2. Research Problem Statement 2
  1.3. Purpose 3
  1.4. Research Framework 4
  1.5. Research Questions 6
  1.6. Data Collection 6
  1.7. Expected Results and Criteria for Evaluating Results 7
2. LITERATURE REVIEW 8
  2.1. Nuclear Power Plants Overview 9
  2.2. Accidents within the Nuclear Power Industry 10
  2.3. Governance of Large Multi-Firm Projects 16
  2.4. Project Cost and Schedule 18
  2.5. Representations of Nuclear Risk 20
  2.6. Strategic Fit 20
  2.7. Resilience and Economic Effects 21
  2.8. Resilience and Human Performance 24
    2.8.1. Overall Situational Awareness 26

Chapter Page

2.8.2. Management of Keystone Vulnerabilities....................26

2.8.3. Adaptive Capacity....................26

2.9. Resilience and Human Reliability Analysis 27

2.10. Multi-Unit Nuclear Power Plant Risk.................... 28

2.11. Nuclear Knowledge Management.................... 30

2.12. Delivering the Nuclear Promise and the Standard Design Process 31

2.13. Nuclear Power Plant License Renewal.................... 33

3. RESEARCH METHODOLOGY....................38

3.1. Methodological design and rationale for the design.................... 38

3.2. Proposed Analysis.................... 40

3.3. Research Design and Methods.................... 40

3.4. Subject Matter Expert Reviews 41

4. RESULTS 43

4.1. Part I: Work Breakdown Structure 43

4.2. Part II: Activity Definitions and Estimates.................... 57

4.2.1. Pre-Job Brief....................62

4.2.2. Procedure Use and Adherence 63

4.2.3. Project Definition and Pre-Design Walkdown....................64

4.2.4. Design Inputs 67

4.2.5. Identify New and/or Update Affected Design Documents....................69

4.2.6. Drawings 70

4.2.7. Calculations....................73

Chapter Page

4.2.8. Technical Reports 74

4.2.9. Specifications 75

4.2.10. Plant Operating Procedures 75

4.2.11. Training Materials 76

4.2.12. Design Basis Documents 77

4.2.13. Installation Instructions 78

4.2.14. 10 CFR 50.59/72.48 Review 79

4.2.15. Programs Impact Review 82

4.2.16. Design Reviews 83

4.2.17. Estimates for Next Phases 84

4.2.18. Conceptual Impact Review Meeting 85

4.2.19. Conceptual Design Estimate 86

4.2.20. Conceptual Design Schedule 88

4.3. Part III: Risks 91

4.3.1. FMEA Severity Scale 94

4.3.2. FMEA Likelihood of Failure Scale 96

4.3.3. FMEA Opportunity for Detection Scale 98

4.3.4. Resources 100

4.3.5. FMEA for Define Project 101

4.3.6. FMEA for Walkdowns 104

4.3.7. FMEA for Design Inputs 107

4.3.8. FMEA for New Drawings 109

Chapter Page

4.3.9. FMEA for Impacted Drawings 112

4.3.10. FMEA for Drawing Peer Review..115

4.3.11. FMEA for Calculations..118

4.3.12. FMEA for Calculation Peer Review 121

4.3.13. FMEA for Identification of Impacted Procedures 124

4.3.14. FMEA for Design Basis Documents...126

4.3.15. FMEA for Bill of Materials 128

4.3.16. FMEA for 50.59/72.48 Review 131

4.3.17. FMEA for SAR Update 134

4.3.18. FMEA for Programs Impact Review 136

4.3.19. FMEA for SME Internal Review..139

4.3.20. FMEA for Next Phase Estimate...141

4.3.21. FMEA Conceptual Design Meeting...144

4.3.23. Risk Priority Number...144

5. CONCLUSIONS...146

5.1. Conclusions and Recommendations 146

5.2. Limitations and Future Research 149

5.3. Contribution to the Engineering Management Field of Knowledge............................... 150

REFERENCES 152

APPENDIX A...157

APPENDIX B 162

APPENDIX C 168

Page

APPENDIX D 175

VITA 178

LIST OF TABLES

Table Page

1. Subject Matter Expert Review Form 42
2. Estimate for Project Definition and Walkdowns 67
3. Estimate for Design Inputs 69
4. Estimate for Drawings and Peer Reviews 72
5. Estimate for Calculations 74
6. Estimate for Procedures 76
7. Estimate for Design Basis Documents 77
8. Estimate for Bill of Materials 79
9. Estimate for 50.59/72.48 Review 81
10. Estimate for Programs Impact Review 83
11. Estimate for SME Internal Review 84
12. Estimate for Next Design Phase 85
13. Estimate for Conceptual Design Meeting 86
14. Complete Estimate for Conceptual Design Phase 87
15. FMEA Severity Scale 95
16. FMEA Likelihood of Failure Scale 97
17. FMEA Opportunity for Detection Scale 99
18. Failure Modes, Effects, Causes, and Recommendations – Define Project 102
19. Failure Mode Ranking Numbers – Define Project 102
20. Failure Modes, Effects, Causes, and Recommendations – Walkdowns 105
21. Failure Mode Ranking Numbers – Walkdowns 105

Table Page

22. Failure Modes, Effects, and Causes, and Recommendations – Design Inputs 107

23. Failure Mode Ranking Numbers – Design Inputs 108

24. Failure Modes, Effects, Causes, and Recommendations – New Drawings 110

25. Failure Mode Ranking Numbers – Design Inputs 110

26. Failure Modes, Effects, Causes, and Recommendations – Impacted Drawings................... 113

27. Failure Mode Ranking Numbers – Impacted Drawings 113

28. Failure Modes, Effects, Causes, and Recommendations –Drawings Peer Review 116

29. Failure Mode Ranking Numbers – Drawings Peer Review... 116

30. Failure Modes, Effects, Causes, and Recommendations – Calculations 119

31. Failure Mode Ranking Numbers – Calculations... 120

32. Failure Modes, Effects, Causes, and Recommendations – Calculation Peer Review 122

33. Failure Mode Ranking Numbers – Calculation Peer Review 122

34. Failure Modes, Effects, Causes, and Recommendations – Identification of Impacted Procedures... 124

35. Failure Mode Ranking Numbers – Identification of Impacted Procedures 125

36. Failure Modes, Effects, Causes, and Recommendations – Design Basis Documents.......... 126

37. Failure Mode Ranking Numbers – Design Basis Documents 127

38. Failure Modes, Effects, Causes, and Recommendations – Bill of Materials........................ 129

39. Failure Mode Ranking Numbers – Bill of Materials 130

40. Failure Modes, Effects, Causes, and Recommendations – 50.59/72.48 Review.................. 132

41. Failure Mode Ranking Numbers – 50.59/72.48 Review 132

42. Failure Modes, Effects, Causes, and Recommendations – SAR Update............................. 134

Table Page

43. Failure Mode Ranking Numbers – SAR Update 135

44. Failure Modes, Effects, Causes, and Recommendations – Programs Impact Review 137

45. Failure Mode Ranking Numbers – Programs Impact Review 137

46. Failure Modes, Effects, Causes, and Recommendations – SME Internal Review 139

47. Failure Mode Ranking Numbers – SME Internal Review 140

48. Failure Modes, Effects, Causes, and Recommendations – Next Phase Estimate/Schedule . 142

49. Failure Mode Ranking Numbers – Next Phase Estimate/Schedule 143

50. List of Power Reactors in the U.S. and Application Status (NRC, 2018) 157

51. Summary of Reactors in the U.S. 161

52. Summary of License Renewal Application Status for Reactors in the U.S. 161

53. Part I SME #1 Comments and Resolutions 162

54. Part I SME #2 Comments and Resolutions 166

55. Part I SME #3 Comments and Resolutions 167

56. Part II SME #1 Comments and Resolutions 168

57. Part II SME #2 Comments and Resolutions 172

58. Part II SME #3 Comments and Resolutions 174

59. Part III SME #1 Comments and Resolutions 175

60. Part III SME #2 Comments and Resolutions 176

61. Part III SME #3 Comments and Resolutions 177

LIST OF FIGURES

Figure Page

1. Research Framework 5

2. Location of U.S. Operating Commercial Nuclear Power Reactors (NRC, 2017) 9

3. Three Mile Island Plant Layout (NRC, 2014) 11

4. Chernobyl RBMK 1000 Plant Layout (NEA and OECD; 2002).. 12

5. Fukushima Daiichi Accident (FEPC, 2018) 13

6. The supply network of the Olkiluoto 3 project (Ruuska et al., 2011) 17

7. The supply network of the Flamanville 3 project (Ruuska et al., 2011).................................. 17

8. Relationship between vulnerability and adaptive capacity of a system in relation to a disaster event (Dalziell and McManus, 2004) 22

9. Relationship between organizational resilience and recovery (Dalziell and McManus, 2004) 23

10. Impact on KPIs as a measure of system resilience (Dalziell and McManus, 2004)............... 24

11. INPO's Performance Improvement Model (INPO, 2006).. 25

12. Example of Multi-Unit Risk 30

13. Work Breakdown Structure Diagram – Overall 51

14. Work Breakdown Structure Diagram – Identify New and/or Update Affected Design Documents 52

15. Work Breakdown Structure Diagram – Installation Instructions 53

16. Work Breakdown Structure Diagram – 10 CFR 50.59/72.48 Review 54

17. Work Breakdown Structure Diagram – Programs Impact.. 55

18. Work Breakdown Structure Diagram – Project Activities 56

Figure Page

19. Standard Design Process Flowchart (SDPRC, 2017) 58

20. Conceptual/Common Design Phase Flowchart (SDPRC, 2017) 60

21. Conceptual Design Schedule – Task, Duration, Resources, and Budget Hours (Microsoft Project) 89

22. Conceptual Design Schedule – Timeline (Microsoft Project) 90

23. Failure Mode Ranking Numbers – Define Project 103

24. Failure Mode Ranking Numbers – Walkdowns 106

25. Failure Mode Ranking Numbers – Design Inputs 108

26. Failure Mode Ranking Numbers – New Drawings 111

27. Failure Mode Ranking Numbers – Impacted Drawings 114

28. Failure Mode Ranking Numbers – Drawings Peer Review 117

29. Failure Mode Ranking Numbers – Calculations 120

30. Failure Mode Ranking Numbers – Calculation Peer Review 123

31. Failure Mode Ranking Numbers – Identification of Impacted Procedures 125

32. Failure Mode Ranking Numbers – Design Basis Documents 127

33. Failure Mode Ranking Numbers – Bill of Materials 130

34. Failure Mode Ranking Numbers – 50.59/72.48 Review 133

35. Failure Mode Ranking Numbers – SAR Update 135

36. Failure Mode Ranking Numbers – Programs Impact Review 138

37. Failure Mode Ranking Numbers – SME Internal Review 140

38. Failure Mode Ranking Numbers – Next Phase Estimate/Schedule 143

39. Failure Modes Severity, Occurrence, Detection Ranks, and Risk Priority Number 145

CHAPTER 1

INTRODUCTION

Much like any other industry in the world, the nuclear power industry in the United States (U.S.) deals with issues such as figuring out how to keep relevant knowledge within the industry and how to modify practices to increase overall success. Due to recent plant closures and matters related to ongoing new nuclear power plant builds, the industry is in need of improving processes with the purpose of completing projects in a shorter time and for a lower cost. This especially holds true for engineering design projects. The efficient and cost-effective development of engineering design modifications could safeguard the resilience and future of the industry.

Instead of building new nuclear power plants, the U.S. nuclear power industry should rely on alternative subsistence strategies. One of these strategies is the successful and cost-effective development and implementation of engineering design modifications to keep plants operating safely and reliably. If utilities can perform these projects in less time and for lower costs, they could become proactive in the enhancement of systems, structures, and components (SSCs). This strategy can, therefore, increase the longevity of nuclear power plants.

With the subsistence of the nuclear power industry in mind, this case study researches the history of nuclear power plants in the U.S., among other topics. Subjects such as governance of large multi-firm projects, project cost and schedule, risk, knowledge retention issues and strategies, initiatives within the industry, and the license renewal process, among others, are discussed.

1.1. Problem Background

The U.S. nuclear power industry may require large-scale design modifications that call for a combination of engineering and project management knowledge and experience to be successful. Project management consists of a comprehensive plan involving a well-defined work breakdown structure (WBS), clear timelines, available resources, and a broad understanding of potential risks. At the same time, technical knowledge in the engineering field is essential. Due to the uniqueness of nuclear power technology, vast regulation, and the continuous effort to maintain safety as paramount, engineering design projects can also be considered unique. The uniqueness of engineering projects within this industry makes the documentation of knowledge an essential step towards subsistence.

1.2. Research Problem Statement

The development of an engineering design modification involves various elements such as experienced resources with knowledge of the problem and a comprehensive project plan. In situations like the 2011 Fukushima response, where the entire U.S. industry set goals to improve plants in specific time periods, it is likely that projects need to be developed in short periods of time and sometimes using less-experienced resources. As a result, and since at times the procedures to follow do not present a straightforward approach on how to accomplish individual activities, a clearly-defined example of an engineering design project is needed. In other words, the industry is in need of a guide on engineering modifications that can be used by experienced resources and entry-level resources alike.

This paper focuses on the development of a case study for an engineering design modification for a nuclear power plant that can be used as an example for developing other engineering projects. The study will focus on, not only explaining what activities need to be completed but how to accomplish them successfully.

The results of this research will provide the nuclear industry with an innovative and reliable tool to be used to develop engineering design modifications in the future. The case study can later be used as an example to build case studies aimed at other industries. This new tool will not only benefit the nuclear industry but will also help others trying to develop a successful engineering design project.

1.3. Purpose

The primary purpose of this paper is to capture the knowledge related to the development of engineering design modification projects for nuclear power plants as a knowledge retention tool for the U.S. nuclear power industry and is achieved by:

1. Developing a comprehensive work breakdown structure for an engineering design project,
2. Providing descriptions of each activity, resources needed, and activity durations, and
3. Identifying potential risks involved with each activity and providing a means to eliminate or mitigate those risks.

1.4. Research Framework

This research project intends to build a case study for the project design phase of engineering design modifications. The resulting case study will serve as a guide for the development of successful engineering projects for nuclear power plants. The concepts described previously are shown graphically in Figure 1.

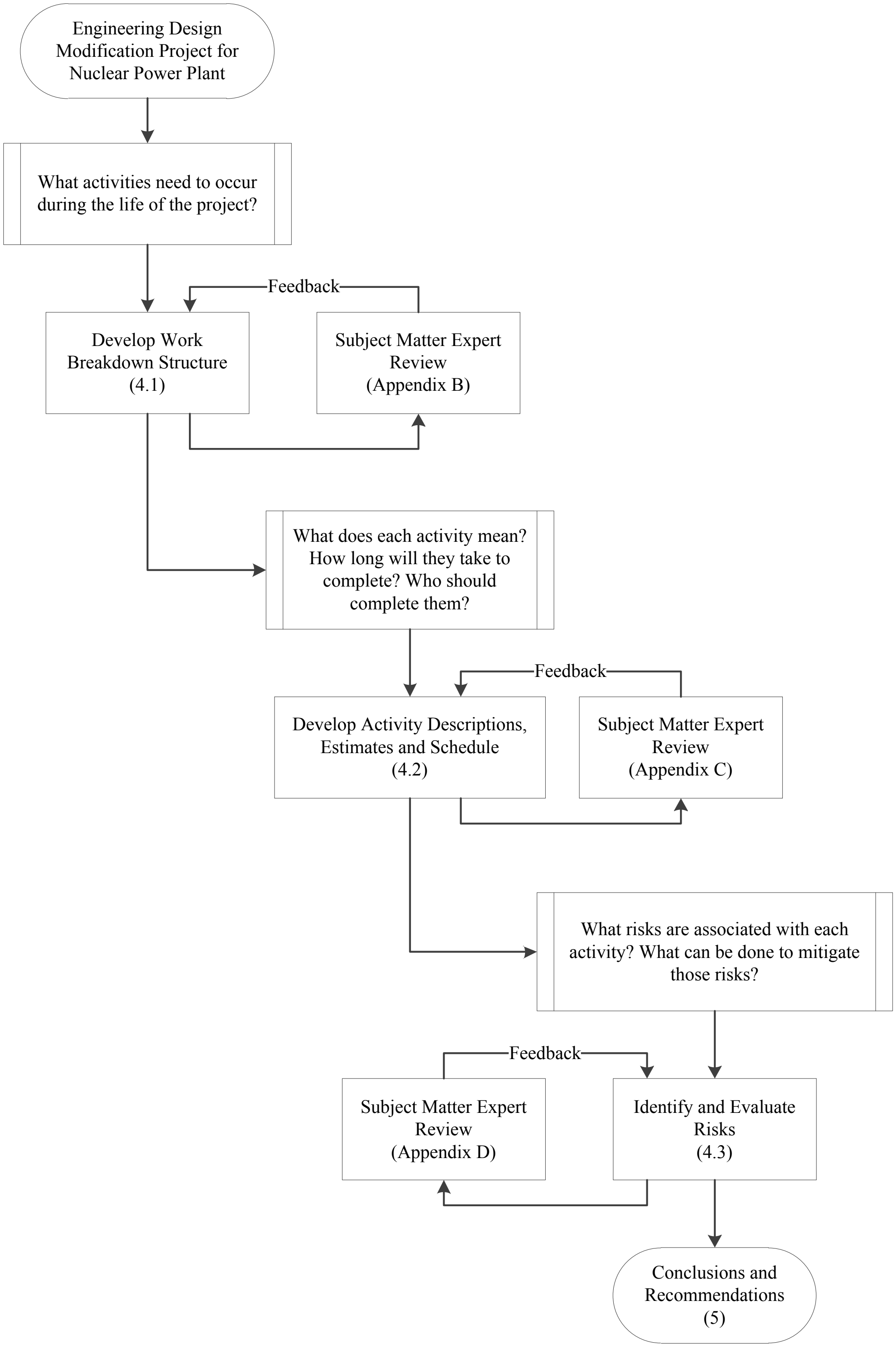

Figure 1. Research Framework

1.5. Research Questions

Once the purpose of the project is addressed, the following research questions will be answered:

1. How is a comprehensive work breakdown structure for an engineering design project within the nuclear industry structured?
2. What processes should take place to deliver a successful project?
3. What risk(s) could be present? What is the recommended risk response? How can these risks impact the overall success of the project?

The resulting case study will be a guideline that can be used to plan successful engineering design projects for nuclear power plants, specifically from the architectural engineering (AE) company's standpoint, rather than from a utility standpoint. Ultimately, the use of the case study can decrease the learning curve needed to complete an engineering design project successfully, and consequently, reduce utilities' operating costs. This case study will, therefore, contribute to the Delivering the Nuclear Promise strategic plan (NEI, 2016).

1.6. Data Collection

The experimental procedure for this study is centered on providing different person-hour estimates and potential risks to different project activities. Data will consist of experience and feedback from peers in the nuclear power industry.

1.7. Expected Results and Criteria for Evaluating Results

The final product consists of a scope-specific case study that can be customized for specific project scopes. A project work breakdown along with cost estimates and activity durations are provided. The criteria to be used to evaluate the results are as follows:

1. Is the case study comprehensive enough that it can be used by an entry-level engineer to develop a design project?
2. Can the case study be modified to accommodate different applications or scopes?

CHAPTER 2

LITERATURE REVIEW

The literature review for this doctoral dissertation focuses on subjects such as the history of nuclear power plants in the U.S., projects, knowledge, risk, and resilience. Each topic is reviewed to gain the necessary background to develop and justify this research project.

The Nuclear Power Plants Overview section gives a broad synopsis of nuclear power plants in the U.S. and a brief description of plant designs such as pressurized water reactors and boiling water reactors. The primary purpose of this section is to provide the reader with the necessary background information to follow this research project. The Accidents in the Nuclear Industry section discusses the nuclear events that have shaped the U.S. nuclear industry; the Three Mile Island (1979), Chernobyl (1986), and most recently, the Fukushima Daiichi (2011) event, are discussed. The License Renewal section provides a brief description of the license renewal process in the U.S. and outlines how it is addressed by nuclear utilities. The governance of large multi-firm projects section describes the interaction of multiple firms working on a single project for nuclear power plants. The project cost and schedule section provide an overview of how educated guesses on cost and schedule affect project's overall risks. The strategic fit section discusses how strategic fit affects the success of a company. The subsequent sections focus on the topic of resilience and how it relates to economic effects, human performance, and the human reliability analysis. These sections are followed by a discussion of risk for multi-unit nuclear power plants. The topic of knowledge management within the nuclear industry is later discussed. This literature review concludes by considering the Delivering the Nuclear Promise strategic plan and the Standard Design Process, which is the focus of this research project's case study.

2.1. Nuclear Power Plants Overview

Nuclear Power Plants (NPP) are power generating stations that use radioactive material (i.e., uranium) to produce heat in a nuclear reactor. There are two types of NPPs in operation within the United States (U.S.): boiling water reactors (BWRs) and pressurized water reactors (PWRs). There is a total of 99 NPPs licensed to operate in the U.S. of which 34 are BWRs and 65 are PWRs (NRC, 2017). The locations of the plants are shown in Figure 2.

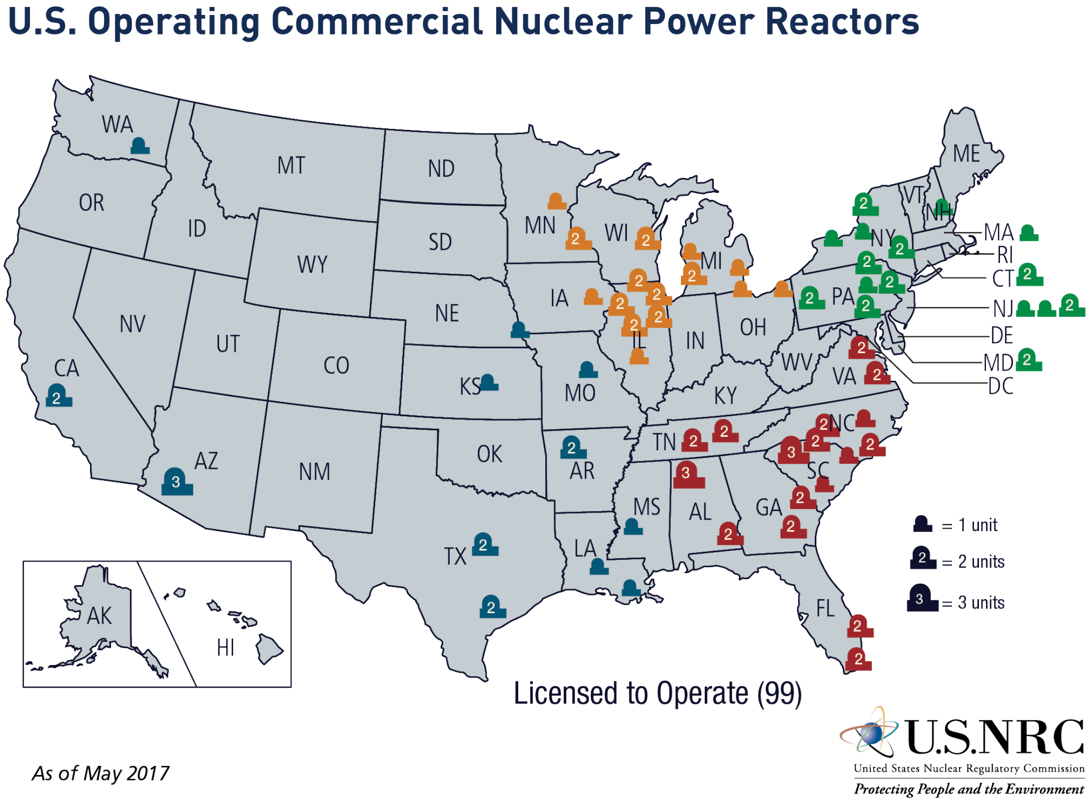

Figure 2. Location of U.S. Operating Commercial Nuclear Power Reactors (NRC, 2017)

BWR plants consist of one thermodynamic cycle composed mainly of a reactor, reactor coolant pumps, feed pumps, turbines, condenser, and a generator. Within the reactor water is boiled, therefore the term BWR, and steam is produced. Since there is only one cycle the steam used to move the turbine is contaminated (i.e., radioactive). A PWR plant consists of two thermodynamic cycles. The first cycle includes the reactor, reactor coolant pumps, feed pumps, steam generators, and a pressurizer. The second cycle consists of the steam generators, turbines, condenser, and the generator. Water is heated to elevated temperatures in the reactor and maintained at high pressure by the pressurizer to avoid boiling. The steam generators use the hot water (i.e., reactor coolant) to produce steam. The reactor coolant flows through the inside of the steam generator tubes, and the steam flows through the outside of the tubes; therefore, the contamination of the reactor coolant is not transferred to the steam.

Nuclear power is considered clean and reliable energy since no greenhouse gases are released, and power is generated at high-efficiency levels. Because of its highly radioactive fuel and significant consequences in case of an accident, safety is the foremost important aspect of nuclear technology.

2.2. Accidents within the Nuclear Power Industry

In the history of NPPs, there have been a series of accidents that have shaped the industry. The most significant being Three Mile Island (1979), Chernobyl (1986), and most recently, Fukushima Daiichi (2011).

- Three Mile Island (1979) – The Three Mile Island (TMI) NPP is a two (2) unit PWR plant located near Middletown, PA (Figure 3). The TMI unit 2 accident is so far the most serious nuclear accident in the history of the United States. The cause of the accident was a combination of personnel error, design deficiencies, and component failures (NRC, 2014), which created a deficiency in the plant's cooling system that led to a partial meltdown of the reactor core and a small release of radioactivity.

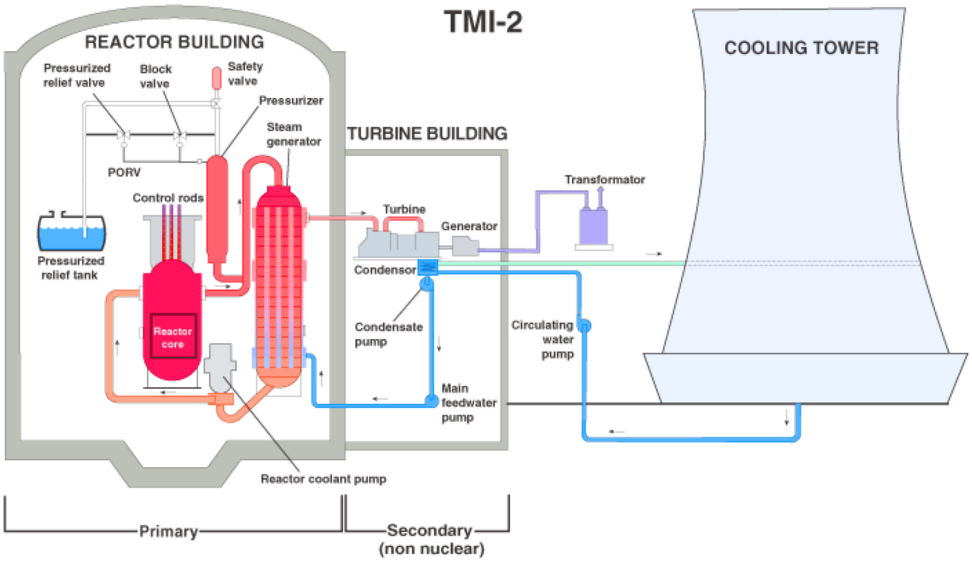

Figure 3. Three Mile Island Plant Layout (NRC, 2014)

- Chernobyl (1986) – The Chernobyl NPP was a 4 unit pressurized water-cooled reactor plant (unique soviet RBMK-1000 design) located in Chernobyl, Ukraine (Figure 4). The Chernobyl Unit 4 accident caused by a sudden surge of power, destroyed the reactor and released massive amounts of radioactive material into the environment (NRC, 2014).

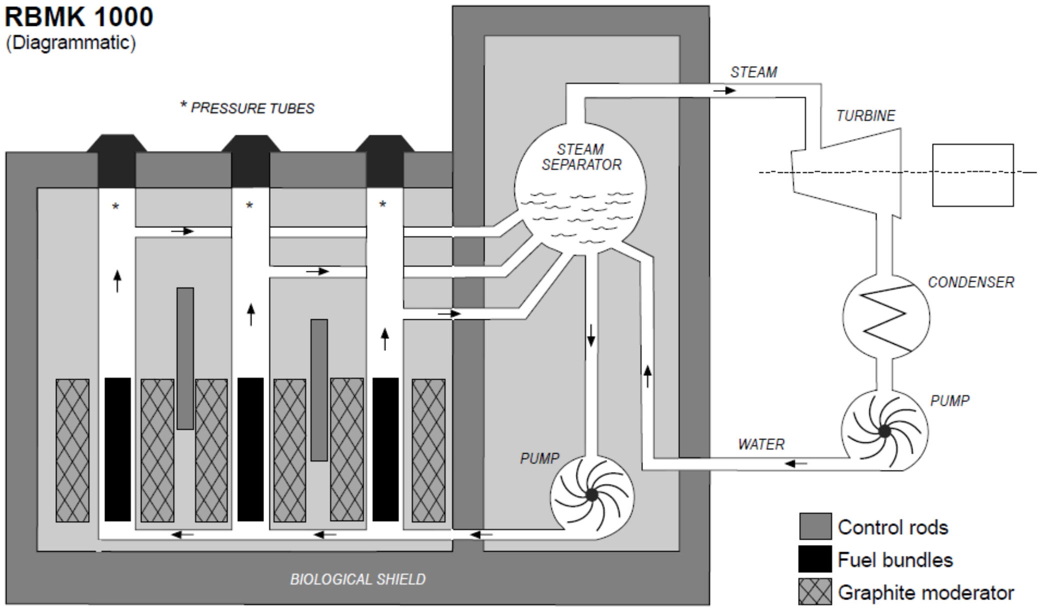

Figure 4. Chernobyl RBMK 1000 Plant Layout (NEA and OECD; 2002)

- Fukushima Daiichi (2011) – The Fukushima Daiichi NPP is a 6-unit BWR plant located in the Futaba District of Fukushima Prefecture, Japan (Figure 5). The cause of the Fukushima accident was a 9.0 magnitude earthquake that created a 15-meter tsunami. The events caused loss of offsite power to the station and eventually the partial meltdown of 3 reactors and off-site release of radioactive material.

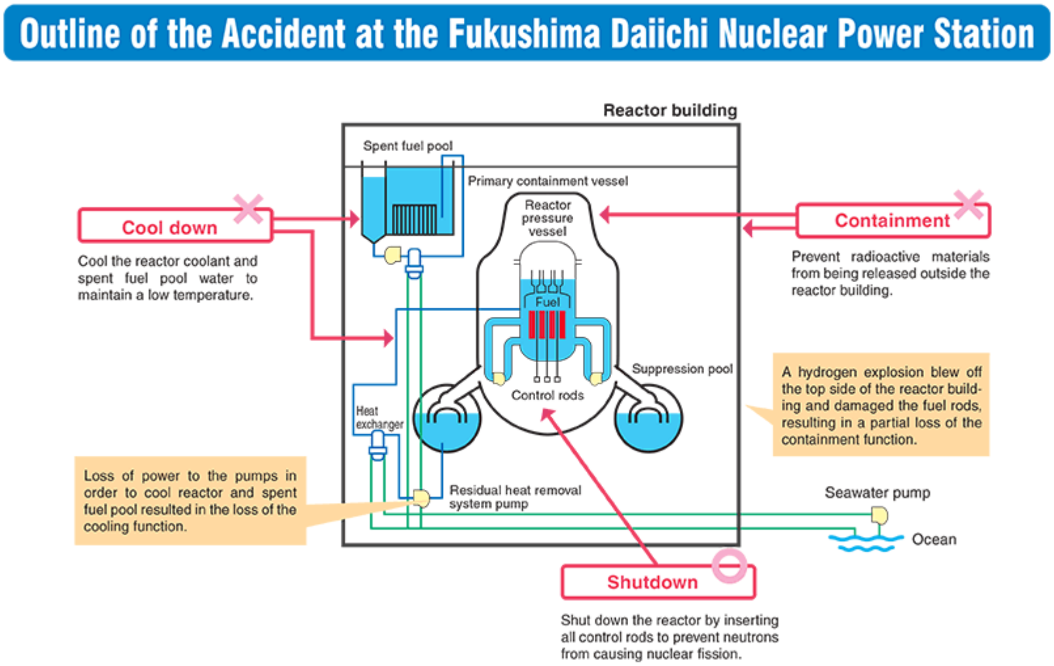

Figure 5. Fukushima Daiichi Accident (FEPC, 2018)

The Fukushima Daiichi event in 2011 is the most recent nuclear event. In March 2011 a 9.0 magnitude earthquake created a 15-meter tsunami that struck the shore of Japan. At the time of the earthquake, 11 reactors from four plants were in operation in Japan. All of the reactors proved to be seismically robust by automatically shutting down and following emergency procedures. Right after the earthquake, the 15-meter (i.e., 49.2-ft) tsunami struck. The flooding caused a loss of offsite power at the Fukushima Daiichi plant. As a result, the emergency diesel generators took over powering the plant and supporting the plant cooling efforts. The tsunami caused flooding which eventually took the diesel generators out of service, impeding the cooling efforts. Even though alternate methods were implemented, such as dumping sea water in the damaged reactors, the strategies were not sufficient. The lack of cooling water caused the fuel to overheat and eventually caused a core meltdown which later initiated the release of radioactive material. Most of the radioactive releases were created by the lack of cooling water on fuel stored in the spent fuel pool.

As a result of the Fukushima event, the U.S. NRC activated and staffed its Emergency Operations Center in Maryland to closely monitor the Japan events and assess the potential impact on U.S. nuclear plants and materials (NRC, 2015). The NRC also established a taskforce to determine lessons learned from the accident and determine if any NRC regulations needed additional measures to ensure the safety of nuclear power plants in the U.S. This taskforce created a series of recommendations which consist of a series of walkdowns and modifications to be done at the nuclear power plants. As a result of the taskforce

> recommendations, the NRC issued the first regulatory requirement based on lessons learned from the Fukushima event in the form of Order EA-12-051, “Issuance of Order to Modify Licenses with Regard to Reliable Spent Fuel Pool Instrumentation”. Since then, projects have been developed, and are being implemented, at nuclear power plants to comply with this NRC order.

All of the described accidents have a shared variable; they all shaped the U.S. nuclear industry we have today. The Three Mile Island accident resulted in the establishment of the Institute of Nuclear Power Operations (NRC, 2014), founded in December 1979 (INPO, 2017). The Chernobyl accident resulted in improvements to nuclear reactors’ operating and emergency procedures. The Fukushima accident resulted in the issuance of order EA-12-049, Issuance of Order to Modify Licenses with Regard to Mitigation Strategies for Beyond-Design-Basis External Events, on March 12, 2012. This order imposes the need for guidance and strategies to prevent fuel damage in the reactor and spent fuel pool (SFP) with a loss of power, motive force and normal access to the Ultimate Heat Sink. The NRC provided an acceptable approach which was outlined in Interim Staff Guidance JLD-ISG-2012-01 issued in August 2012. The Interim Staff Guidance endorses the methodologies described in NEI 12-06 Revision 0, Diverse and Flexible Coping Strategies (FLEX) Implementation Guide, with exceptions, additions, and clarifications. Plants in the U.S. approached the order differently but all developed FLEX strategies to implement it.

The process of updating plants to support these strategies required extensive project management efforts and collaboration between organizations and firms. The following section discusses the governance of large multi-firm projects such as FLEX.

2.3. Governance of Large Multi-Firm Projects

The 2011 paper, “A new governance approach for multi-firm projects: Lessons from Olkiluoto 3 and Flamanville 3 nuclear power plant projects,” by Ruuska et al., focuses on the construction projects of the Olkiluoto 3 plant in Finland and the Flamanville 3 plant in France. Both plants are turnkey plants supplied by Areva, a French nuclear company. For the projects to take place, in both instances, various other entities or companies were involved including the builders, owner, regulating agencies, and turbine suppliers. One of the essential aspects discussed in this paper is how relationships between the entities involved in the project affect the overall result of the project. Figure 6 and Figure 7 show the supply networks of the Olkiluoto 3 and Flamanville 3 projects. Even though the Flamanville 3 network is more complex (i.e., more relationships) the project was more successful than the Olkiluoto 3. The reason for this mainly was the good relationship between Électricité de France (EDF), the owner and architect/engineer, and Areva, the nuclear supplier. Both of these are French companies that have worked together on previous projects. Therefore, they understand how one another work, and they work together to deliver a successful project. In the case of Olkiluoto 3, Teollisuunden Voina (TVO), the owner, had never worked with Areva, making this a first-of-a-kind relationship.

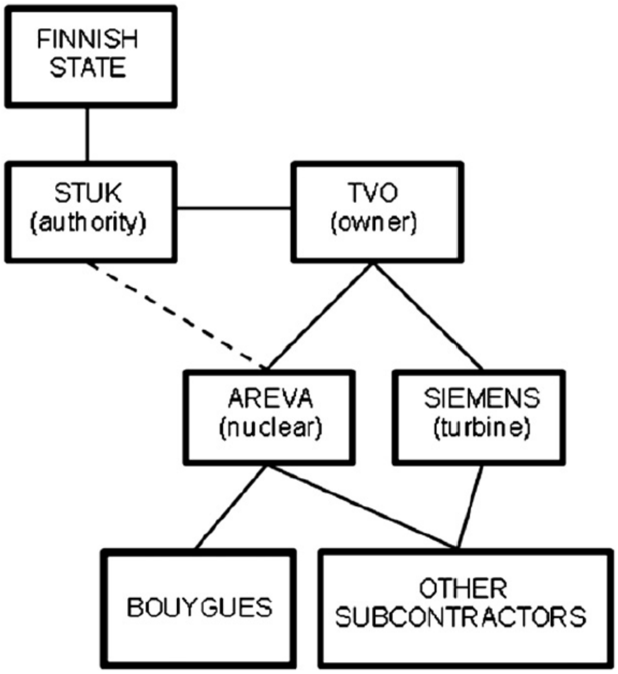

Figure 6. The supply network of the Olkiluoto 3 project (Ruuska et al., 2011)

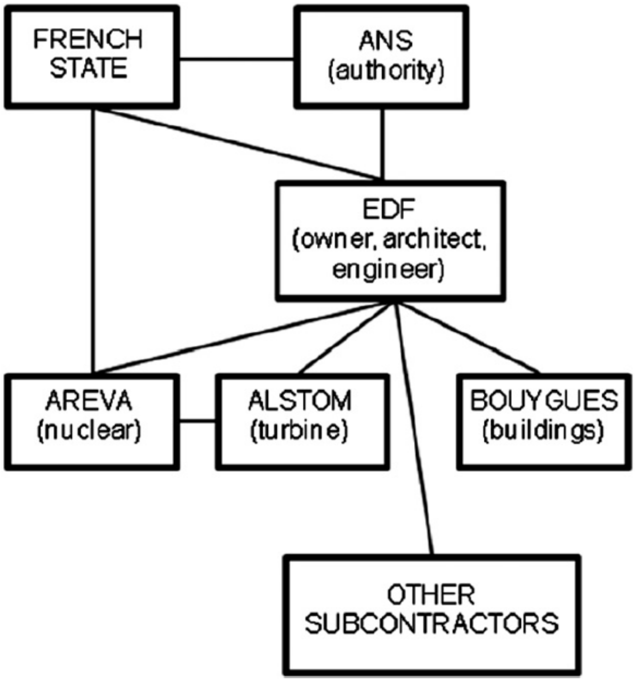

Figure 7. The supply network of the Flamanville 3 project (Ruuska et al., 2011)

The paper concludes by giving four implications for changes in governing large projects that may possess the potential for enhancing both effectiveness and efficiency within large and complex projects (Ruuska et al., 2011). These are (Ruuska et al., 2011):

1. shift focus from a hierarchical contact organization to a supply network organization,
2. project governance should shift from price and mechanism to relationships and self-regulation,
3. view large multi-firm projects as incorporated in the business interest and not as temporary endeavors, and
4. focus on an open system view of managing projects instead of a narrow view.

The application of these implications to a design modification can improve the efficiency of such projects. At the same time, some of the potentials risks involved with the interaction of various firms can be mitigated or even eliminated, therefore improving the project's cost and schedule.

2.4. Project Cost and Schedule

In his 2014 paper, "In the Land of the Blind the One-Eyed Man is King: Using Advanced Scheduling and Simulation Techniques to Control Project Risk," Shannon describes how estimating cost and schedule are all educated guesses (2014), and not accurate or realistic representations of how long the projects are going to last, or how much they are going to cost. He also describes how the accuracy can be enhanced by dividing a big project into smaller manageable scopes. Therefore, by better "guessing" the smaller scopes we can come up with better "guesses" for the overall project, just by adding the smaller scopes up. The downside of following this approach is that rounding up errors are accumulated and can inflate the final estimates for the projects.

Later, Shannon describes how errors in estimation can be introduced into project estimates by using the following project management methods: analogy, parametric estimates, historical data, expert opinion, and the “Delphi” technique. All of these methods are likely to introduce errors due to, most commonly, lack of data appropriate to the domain being estimated (Shannon, 2014). The best way to overcome this issue is to not use single-value data; instead, data ranges are most appropriate. Shannon describes that data ranges should consider a minimum value, a most likely value, and a pessimistic “worst case” value (2014).

All of the errors discussed that could be introduced into an estimate, build up into the uncertainty of that estimate. Another uncertainty is added by risks. These risks can be categorized as technical, cost, and schedule risks. These risks can be managed by the following six steps:

1. identify the risks,
2. document the risks,
3. characterize the risks,
4. prioritize the risks,
5. develop risk management strategies, and
6. monitor and control risks.

Regarding identifying risks, considering risk scenarios instead of single risks gives results that are closer to reality (T.-H. Nguyen et al., 2013). After these steps are followed, a more comprehensive estimate for cost and schedule can be developed that includes the effects of the identified risks. This results in better estimates that are more than just “educated guesses.”

2.5. Representations of Nuclear Risk

In the paper, “Environments, Risks, and the Limits of Representation: Examples from Nuclear Energy and Some Implications of Fukushima,” Kinsella (2012) discusses how risks in the nuclear industry, concerning unusual events, are often not represented correctly. Because of this, some of the events are sometimes under or overestimated. An example given, not directly related to nuclear power, is the production of nuclear warheads for the Cold War. The number of warheads needed was considerably overestimated (Kinsella, 2012). Under or overestimation can mainly occur when there is not enough knowledge on a topic to model, or estimate, the work.

Regarding nuclear power, Kinsella continues by discussing the effects of the Fukushima events on the industry. He explains how lessons learned from the Fukushima events only focus on the triggering events of earthquake and tsunamis but fail to identify other possible events due to the lack of knowledge. Therefore, the representation of this risk is limited only to the known information.

2.6. Strategic Fit

Van Aduard de Marcedo-Soares et al. (2009) discuss in their paper, “Strategic Fit of Project Management at a Brazilian State-Owned Firm: The Case of Electronuclear,” how project management strategic fit affect the success of a firm or company. In the paper, Van Aduard de Marcedo-Soares et al. give the example of the Brazilian nuclear firm Eletrobrás Termonuclear S.A. – Eletronuclear, or just Eletronuclear. The article shows how the lack of strategic fit ends up having a negative impact [on a company’s] performance and competitiveness (Marcedo-Soares et al., 2009). The research focused on employee interviews to understand the firm’s organizational culture and characterize employee’s perception of strategic fit. Various weaknesses on the organization were identified. One of those weaknesses is the lack of project management culture, involving policies, procedures and best project management practices (Marcedo-Soares et al., 2009). Within the nuclear industry, procedure use and adherence is one of the human performance safety culture's most important behaviors.

2.7. Resilience and Economic Effects

Dalziell and McManus describe the economic effects of events on organizations in their 2004 paper on resilience, vulnerability, and adaptive capacity. They also emphasize the need for resilient organizations to have resilient communities. The first step to evaluate these organizations is to apply a system analysis since organizations are dynamic complex systems. The most important aspect is not to isolate components; instead, analyze components as a whole since understanding the relationships between various components in a system is the best way to analyze the system. System resilience is composed of two main terms, vulnerability and adaptive capacity.

> *Vulnerability* – the human product of any physical exposure to a disaster that results in some degree of loss, combined with the human capacity to withstand, prepare for and recover from that same event (Dalziell and McManus, 2004).
>
> *Adaptive Capacity* – reflects the ability of the system to respond to changes in its external environment, and to recover from damage to internal structures within the system that affect its ability to achieve its purpose (Dalziell and McManus, 2004).

Dalziell and McManus (2004) also describe resilience as the overarching goal of a system to continue to function to the fullest possible extent in the face of stress to achieve its purpose, where resilience is a function of both the vulnerability of the system and its adaptive capacity. They also describe vulnerability and adaptive capacity as the ease with which the individual, community or organization is pushed into this new state is a measure of their vulnerability, while the degree to which they can cope with that change is a measure of their adaptive capacity. These concepts are shown in Figure 8. The relationship between resilience and recovery is also discussed. Figure 9 describes the relationship.

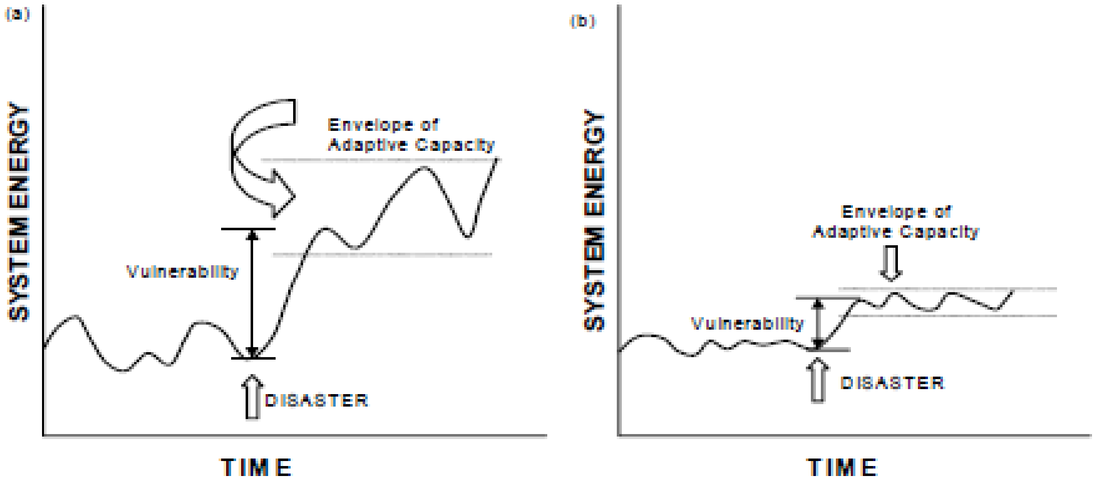

Figure 8. Relationship between vulnerability and adaptive capacity of a system in relation to a disaster event (Dalziell and McManus, 2004)

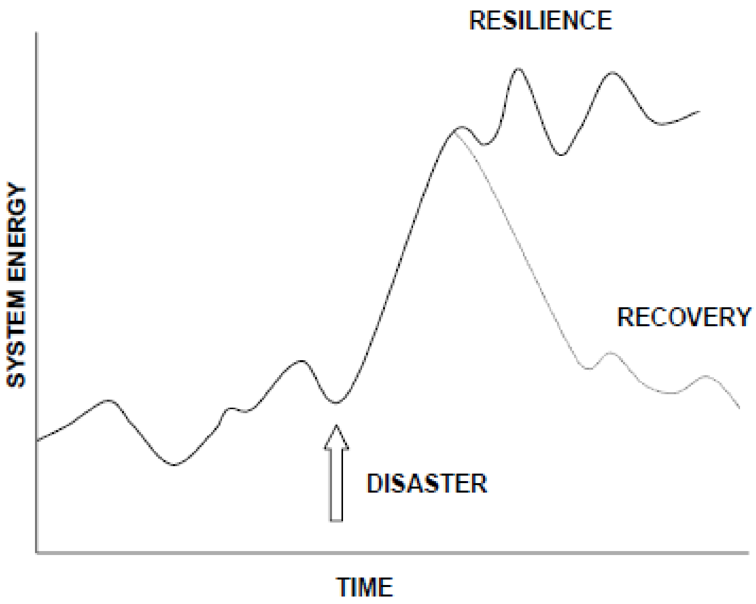

Figure 9. Relationship between organizational resilience and recovery (Dalziell and McManus, 2004)

Overall system resilience is then evaluated using an organization's key performance indicators (KPIs) and the effects of changes in those indicators as a relationship of time. The area under the ΔKPI versus time curve is designated as the organization's (i.e., the system's) resilience (Figure 10).

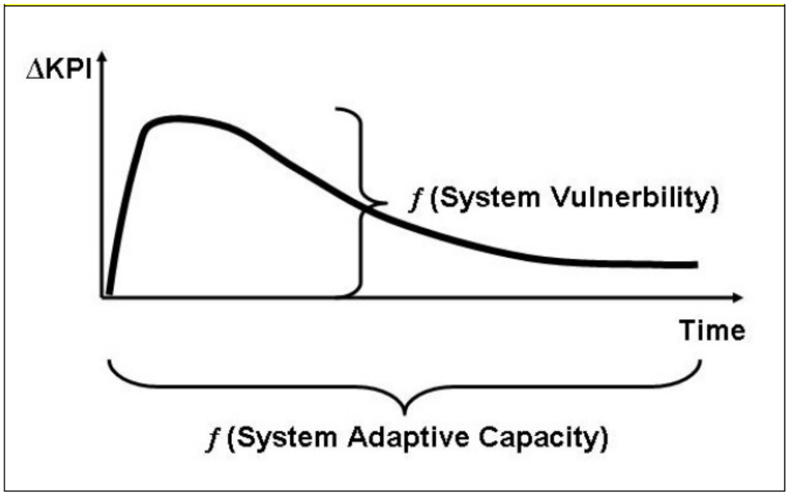

Figure 10. Impact on KPIs as a measure of system resilience (Dalziell and McManus, 2004)

For Nuclear Power Plants the term Key Performance Indicator is directly related to the concept of Human Performance (HU).

2.8. Resilience and Human Performance

Resilience engineering suggests that a company must recognize, adapt to, and absorb challenges that fall outside the scope of its design and historical experiences (Huber et al., 2008). This is also the main purpose of Human Performance (HU). As shown in INPO's Performance Improvement (PI) Model (INPO, 2006), Figure 11, the main areas of HU are performance monitoring (finding gaps); analyzing, identifying, and planning solutions (analyzing actions); and finally implementing solutions (fixing results).

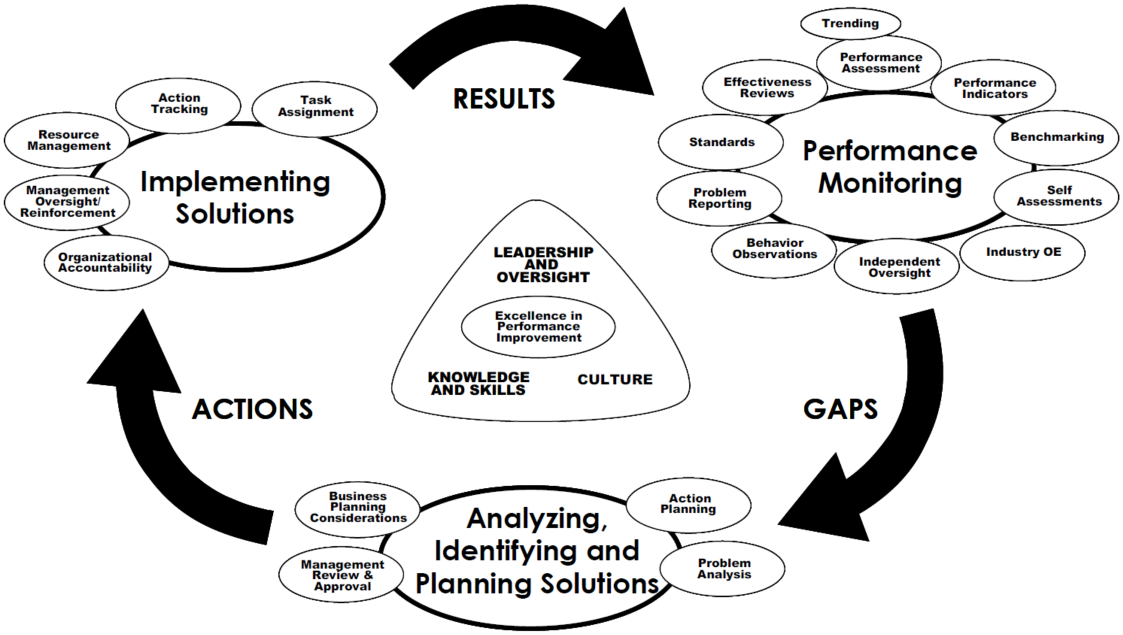

Figure 11. INPO’s Performance Improvement Model (INPO, 2006)

McManus, Seville, Vargo, and Brunsdon (2008) define resilience of an organization as a function of the overall situation awareness, management of keystone vulnerabilities, and adaptive capacity of an organization in a complex, dynamic, and interdependent environment. As mentioned previously, a nuclear power plant is a complex, dynamic, and interdependent environment. Now, let’s look closely at this definition of organizational resilience and the various HU tools that satisfy it.

2.8.1. Overall Situational Awareness

Tools such as task-review, technical task review, job-site review, questioning attitude, and three-way communications, all under the fundamental HU tools for workers, engineers and knowledge workers, describe the overall situational awareness variable. When looking at INPO's PI model, we can locate resilience overall situational awareness under the performance monitoring area.

2.8.2. Management of Keystone Vulnerabilities

Tools such as pre-job briefing, concurrent verification, turnover, and post-job reviews, all under the conditional and verification HU tools for workers, engineers and knowledge workers, address the management of keystone vulnerabilities variable. This variable is the analyzing, identifying, and planning solutions under INPO's PI model. This variable also involves the tracking and trending of HU KPIs.

2.8.3. Adaptive Capacity

Adaptive capacity is closely related to the communication of HU KPIs and is the implementing solutions area under INPO's PI model. By communicating HU events and HU clock resets, personnel become aware of the HU status in their plant and/or department and become more conscious of error likely situations. By doing this, events can be prevented. Through communication, interim solutions and corrective actions to previous events are also shared.

Human Performance can be incorporated into the analysis of resilience by integrating it to the Human Reliability Analysis (HRA). HRA is characterized by the NRC (2005) as the lack of consistency among practitioners on the treatment of human performance in the context of a probabilistic risk assessment (PRA).

2.9. Resilience and Human Reliability Analysis

Resilience is directly related human reliability analysis (HRA). Boring (2010) defines human error as any action or inaction on the part of an individual that decreases the safety of the system with which he or she is interacting. HRA consists of three different stages:

- Modeling of the potential contributors to human error
- Identification of the potential contributor to human error, and
- Quantification of human errors

In the human factors world, HRA is considered unique since it focuses on prediction rather than description. HRA predicts vulnerabilities in human actions. These vulnerabilities are then analyzed to establish recovery actions which feed into resilience engineering. Boring (2010) considers resilience engineering as a young field that has attracted considerable attention already and is being heralded as a significant way of thinking about safety. He also describes the basis of resilience engineering as a science to optimize safety, not to undermine existing safety.

Resilience engineering is a complementary undertaking of HRA. HRA's primary purpose is the human recovery to achieve system safety, which is the main purpose of resilience engineering. Boring (2010) describes what each of the methods brings to the other.

What HRA brings to resilience:

- Quantitative emphasis
- Performance shaping factors
- Systemic view

What resilience brings to HRA:

- Unexampled events
- Dynamic events

The interactions between resilience and HRA are the characterization of system safety. Overall, by improving the HRA terms within a PRA model, the resilience of a nuclear power plant can be achieved.

2.10. Multi-Unit Nuclear Power Plant Risk

Multi-unit risk has recently become a topic of interest when it comes to PRA and is also known as multi-unit probabilistic risk assessment (MUPRA). Kim et al. (2016) define multi-unit risk as the risk associated with multiple units regardless of the types of radiological sources (i.e., reactor or spent fuel pool).

Based on a recent study of U.S. license event reports (LERs) submitted to the NRC between 2000 and 2011, 9% of the LERs submitted affected multiple sites with the most common cause of these events being organizational dependencies. This percent accounted for 41% of the total 9% (Kim et al., 2016). Some of the organizational dependencies that are directly related to the design phase of a project include (Kim et al., 2016):

- Design issue that affects multiple units
- Incorrect calculation that is used on multiple units
- Incorrect technical specifications that have been mirrored for multiple units
- Incorrect engineering judgment that has been applied to multiple units
- Poor safety culture which leads to errors of judgment and execution across the organization

- Latent failures present in the site systems, structures, and components (SSCs) (e.g., design issues or incorrect engineering analysis applied to multiple units, maintenance errors repeated on several units).

Even though all of the mentioned organizational dependencies are relevant to the design phase of nuclear projects, latent failures in the site SSCs might be the most important one. Aside from natural events that can affect multiple units, regardless of the site, common SSCs between units pose the greatest risk of failure and can be the cause of the rest of the organizational dependencies.

Out of the 100 NPPs licensed to operate in the U.S., 25 are single-unit sites, nine units are part of a three-unit site (3 sites), and 66 units are part of dual-unit sites (33 sites) (NRC, 2017). As of early 2018 there are no sites with more than 3 operating units in the U.S. Soon, as early as 2020, with the construction of the Units 3 and 4 at Vogtle in Georgia, the U.S. will count with 25 single-unit sites, 62 units in dual-unit sites (31 sites), 9 units in three-unit sites (3 sites), and 4 units in a four-unit site (1 site), not accounting for any plant closures in the near future. This new scenario will make Vogtle a one of a kind site in the U.S.

With the soon to be U.S. nuclear fleet panorama, multi-unit risk (see Figure 12 for example) is more relevant than ever. Human errors made during the design phase of projects, while they are less influential than the general external events in terms of area and scope (Heo et al., 2016), still pose a great risk of latent failures. Measures need to be put in place to identify these risks early in the design process.

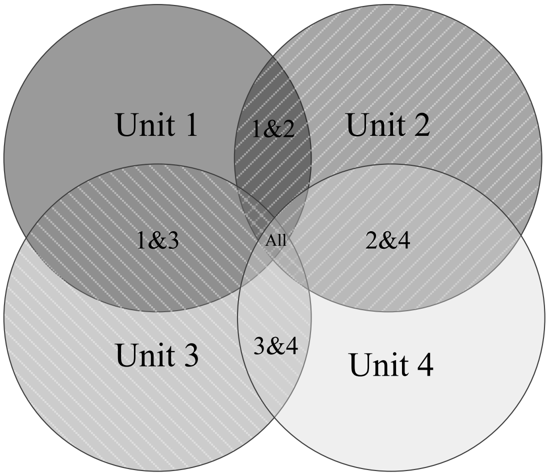

Figure 12. Example of Multi-Unit Risk

2.11. Nuclear Knowledge Management

Knowledge is the correct interpretation of data (Yanev, 2013). The management of nuclear knowledge has become an ongoing issue in the commercial nuclear power industry. This issue emerges from the fact that the nuclear power workforce is aging. The most knowledgeable workers within the industry, many of whom have dedicated their entire professional careers to nuclear and have been around since the design and construction of the majority of nuclear power plants in the U.S., are retiring and taking with them years of knowledge and experience.

Even though processes within the nuclear industry are usually captured in documents such as industry guidelines and procedures (i.e., explicit knowledge (IAEA, 2004)), tacit knowledge is not captured. The International Atomic Energy Agency (IAEA, 2004) defines tacit knowledge as knowledge that is held in a person’s mind. This knowledge is not typically captured or documented and is easy to lose. This tacit knowledge is typically kept by retiring employees and is rarely transferred to new or upcoming employees. The safety of existing and new power plants will directly depend on how we preserve, transfer and further grow nuclear knowledge and expertise worldwide (Yanev, 2013).

One way of retaining tacit knowledge within an organization is to create programs that facilitate the transfer of knowledge. This information can be transferred through training or mentoring. Even though the new nuclear workforce is required to have formal training, this training or education is just the beginning of the training process and much hands-on practical experience is also necessary to gain the required competence (Yanev, 2013) to operate a nuclear power plant safely. On the other hand, mentoring is a key approach to knowledge transfer, which allows for both the explicit and tacit aspects of knowledge to be transferred (Pollack, 2012).

Another way of capturing tacit knowledge is by documenting the knowledge, which is the purpose of this case study, to capture the knowledge related to the development of engineering design projects as a knowledge retention tool for the U.S. nuclear power industry.

2.12. Delivering the Nuclear Promise and the Standard Design Process

Delivering the Nuclear Promise is a strategic plan developed by nuclear energy facilities in the U.S. and led by the Nuclear Energy Institute (NEI) to strengthen the industry’s commitment to excellence in safety and reliability. It assures future viability through efficiency improvements, and drives regulatory and market changes so that nuclear energy facilities are fully recognized for their value (NEI, 2017). In the strategic plan three focus strategies are identified: maintain operational focus, increased value, and improve efficiency (NEI, 2016). As a result of these strategies, four building blocks were developed. These are (NEI, 2016):

- Building Block 1: Analyze cost drivers and identify opportunities to improve efficiency.

- Building Block 2: Leverage federal and state policies to ensure monetary recognition of nuclear energy’s value.
- Building Block 3: Redesign nuclear power plant processes to improve efficiency while advancing the fundamentals of safe, reliable operation.
- Building Block 4: Implement a communications strategy to ensure industry engagement in the initiative.

This case study is directly related to building block 3. One of the objectives of this building block is to develop procedures and processes to facilitate discrete industry efficiency initiatives (NEI, 2016). One of these processes is the engineering design process.

As part of the Delivering the Nuclear Process strategy, NEI has issued a series of more than 40 efficiency bulletins (NEI, 2017) including graded approach to walkdowns (EB 16-02), optimizing FLEX equipment preventive maintenance strategies (EB 16-17), standardization of in-processing training (EB 16-26b), and standard design change process (EB 17-06), among others. Efficiency Bulletin 17-06 (NEI, 2017), Implement Standard Design Process, provides a detailed description of this efficiency opportunity. One of the reasons for implementing this change, which applies to the entire industry, is to address the administrative burden and complexity for developing design changes (i.e., streamline the design process), and avoid increased costs and project delays. As it pertains to AE companies, one of the reasons to implement this change is to avoid having to maintain unique procedures and training to each fleet or site. The selection of design change types is also addressed. This study focusses on full design changes.

The Standard Design Process (SDP) is described in Nuclear Industry Procedure IP-ENG-001 (2017), issued by the Standard Design Process Steering Committee (SDPSC). This procedure is meant to be used in conjunction with site-specific procedures and is based on standard industry guidance, expectations, and operating experience (SDPSC, 2017). The SDP covers guidance for the:

- Initial Scoping Phase
- Conceptual/Common Design Phase
- Detailed Design Phase (i.e., for Design Equivalent Change, Commercial Change, and Design Phase)
- Planning Phase
- Installation/Testing Phase, and
- Design Closure Phase

The scope of this case study will focus on the Initial Scoping Phase, the Conceptual/Common Design Phase, and the Detailed Design Phase for a full design change since it is the most comprehensive of all the change types. This new process will be incorporated into Chapter 4 of this case study.

2.13. Nuclear Power Plant License Renewal

In the United States, nuclear power plants were originally licensed for 40 years. This licensing time limit was chosen as default and was a result of the projected lifetime of fossil plants (Weinberg, 2004), which was the closest benchmark available. Later, the industry determined that nuclear plants were suited to operate for more than 40 years. This resulted in the publication of the original license renewal rule by the Nuclear Regulatory Commission (NRC) in 1991, 10 CFR Part 54. An amended license renewal rule was later issued in 1995.

The license renewal rule governs the issuance of renewed operating licenses and renewed combined licenses for nuclear power plants licensed pursuant to Sections 103 or 104b of the Atomic Energy Act of 1954, as amended, and Title II of the Energy Reorganization Act of 1974 (NRC, 2017). This rule allows nuclear power plants to renew their operating licenses for an additional period of 20 years. The rule also allows for subsequent renewals of 20-year intervals. By the time this report is issued, 84 plants have completed their license renewal application process, leaving 15 plants with applications under review, as future submittals, or with no intent to submit. Appendix A shows a detailed list of nuclear power plants licensed to operate in the U.S. and their license renewal status.

The scope of a plant's license renewal is determined by performing an Integrated Plant Assessment (IPA). This assessment identifies the SSCs (and their functions) requiring aging management to ensure they will be managed to maintain the current licensing basis (CLB) and to ensure that there is an acceptable level of safety during the period of extended operation (NRC, 2017). These SSCs are (NRC, 2017):

1) Those relied upon to remain functional during and following design-basis events (as defined in 10 CFR 50.49 (b)(1)) to ensure the following functions:
    i. The integrity of the reactor coolant pressure boundary;
    ii. The capability to shut down the reactor and maintain it in a safe shutdown condition; or
    iii. The capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to those referred to in § 50.34(a)(1), § 50.67(b)(2), or § 100.11 of 10 CFR, as applicable.

2) All nonsafety-related systems, structures, and components whose failure could prevent satisfactory accomplishment of any of the functions identified in 1).
3) All systems, structures, and components relied on in safety analyses or plant evaluations to perform a function that demonstrates compliance with the Commission's regulations for fire protection (10 CFR 50.48), environmental qualification (10 CFR 50.49), pressurized thermal shock (10 CFR 50.61), anticipated transients without scram (10 CFR 50.62), and station blackout (10 CFR 50.63).

The scope of the IPA typically becomes the scope of a plant’s Aging Management Program (AMP).

A portion of the IPA for license renewal consists of component scoping and screening evaluation, and Aging Management Review (AMR), of a specific system. This is performed for mechanical components, electrical components, and structures. The component scoping and screening evaluation determines which passive long-lived system components are within the scope of the AMP and subject to an AMR. This is typically done by reviewing P&IDs (i.e., process and instrumentation drawings) and performing system walkdowns to confirm P&ID data. The AMR demonstrates that the effects of aging are adequately managed such that the component’s intended function will be maintained consistent with the CLB for the period beyond the 40-year plant design basis. The AMR does the following:

1. Identifies components’ intended functions – For mechanical components intended functions may be pressure boundary and heat transfer, among others.
2. Identifies components’ materials of construction – These may be divided into subcomponents depending on material types. For example, a valve may have a

carbon steel body subcomponent and a stainless steel bonnet subcomponent. A heat exchanger may be divided into shell, tubes, and tube sheet.

3. Identifies components' internal and external operating environments – Some of the environments typically applied are air, air with borated water leakage, raw water, treated water, lubricating oil, soil, and concrete.
4. Assigns AMR groupings (i.e., material and environment combinations), both internal and external – These are identified using guidance from the Nuclear Energy Institute (NEI) described in NEI 95-10. An example of an AMR grouping may be carbon steel in treated water.
5. Determines aging effects requiring management – Some of these are the loss of material (e.g., crevice corrosion, pitting corrosion, general corrosion, microbiological induced corrosion, and cracking, among others).
6. Identifies the programs that will be employed to manage the aging effects – These are identified using guidance described in NUREG-1801 by the NRC, also known as the GALL Report (i.e., Generic Aging Lessons Learned). Some examples of the programs that may apply to mechanical components are Flow Accelerated Corrosion (i.e., XI.M17, referring to the GALL chapter), Boric Acid Corrosion (i.e., XI.M10), External Surfaces Monitoring of Mechanical Components (i.e., XI.M38), and Water Chemistry (i.e., XI.M2).

The process just described is later used to implement an AMP at nuclear power plants. The AMP consists of a series of activities based on the format provided in NEI 95-10 for managing the effects of aging on components (INPO, 2015). The key aspects of the AMP are monitoring or inspecting parameters, acceptance criteria, detection of aging effects, preventive actions, trending, and application of operating experience. As it pertains to engineering modifications, acceptance criteria are the most relevant aspects of the AMP. When acceptance criteria are not met, corrective actions, such as replacement through engineering modifications, need to be put in place to ensure that SSCs are maintained under all CLB design conditions during the period of extended operation, therefore ensuring the longevity of the nuclear power plant.

CHAPTER 3

RESEARCH METHODOLOGY

The following sections describe the methodology to be used to develop a case study for the design phase of engineering projects for nuclear power plants. The research questions, research environment, and experimental procedures will be discussed.

3.1. Methodological design and rationale for the design

The development of this engineering design case study is divided in three parts. Part I (Section 4.1), Work Breakdown Structure, displays a comprehensive work breakdown structure for an engineering project. The information consists of a list of activities that will need to occur throughout the life of an engineering design modification project until completion of the design package. Each activity is descriptive and broken down into sub-activities. The activities range from the development of the project scope to the implementation and close-out of the project. Activities relevant to the development of a conceptual design package are later identified. These activities are the foundation of Part II.

Part II (Section 4.2) of this case study, Activity Definitions and Estimates, consists of providing descriptions to the activities identified in Part I. Person-hour estimates are also assigned. The descriptions and estimates provided are based on a hypothetical project scope defined in Section 4.2 of this case study. This section provides information such as:

- responsible resource,
- estimated person-hours needed to complete the activity,
- possible interactions with other resources,
- required reviews or oversight,

- relationship to other activities, and
- required procedures or forms to be completed.

The results of Part II are captured in tables within Section 4.2 and in a project schedule developed using the Microsoft Projects software. This information can later be used to develop project costs and schedules for other projects.

Part III (Section 4.3), Risks, consists of evaluating each activity described in Part II and identifying potential risks. The activities are evaluated using the Failure Modes and Effect (FMEA) risk assessment tool. The third phase will also evaluate the resilience of the overall project in order to identify potential cost and schedule obstacles.

The described methodology relates to the research questions as follows:

Research Question #1 – How does a comprehensive work breakdown structure for an engineering design project within the nuclear industry look like?

In order to answer this question, a comprehensive list of activities has to be created. Some of these activities include: development of a scope summary, identification of impacted documents, installations instructions, development of drawings, and programs reviews. Sub-activities should also be included in order to facilitate the development of person-hour estimate.

Research Question #2 – What should take place to deliver a successful project?

Each activity listed within the work breakdown structure should be supplemented with a description of what it entails. Industry documents and specific plant procedures can also be referenced within each activity description. Estimated person-hours required to complete each activity should also be included, including responsible resources. Each activity should also include, to the extent possible, lessons learned from industry documents or personal experience, among others.

Research Question #3 – What kind of risk could I face? What risk response can be identified? How can these risks impact the overall success of the project?

The last portion of the case study will focus on what can go wrong with each individual activity. To the extent possible, mitigating strategies for those identified risks should also be provided. If mitigating strategies cannot be provided, then possible consequences of accepting risks should be discussed.

3.2. Proposed Analysis

The experimental procedure for this study is based on identifying activities to be completed within the development phase of an engineering design project in the nuclear industry, describing the activities in detail, providing person-hour estimates for each activity and identifying the potential risks each activity could encounter. The final product consists of a comprehensive case study that can be customized based on specific project applications. Data consists on experience and feedback from Subject Matter Experts (SMEs) in the nuclear industry.

3.3. Research Design and Methods

The design of the research and method to be applied is shown in Figure 1. The research consists of three major parts. A Subject Matter Expert (SME) review is performed after each part is developed.

3.4. Subject Matter Expert Reviews

SME reviews consist of reviewing the content of a specific part. The scope of each review consists of:

- SME Review #1 – Review Part I, Work Breakdown Structure, of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.
- SME Review #2 – Review Part II, Activity Definitions and Estimates, of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.
- SME Review #3 – Review Part III, Risks, of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.

Three SMEs have been chosen to perform the reviews. Each SME has previous experience with design engineering projects within the U.S. nuclear power industry. SMEs are a combination of civil/structural engineer, electrical/instrumentation and controls (I&C) engineer, and project manager. A combination of these types of SMEs will guarantee reviews from different perspectives. As part of the review, SMEs provided professional tittle (including engineering discipline if applicable) and a brief description of their experience as it relates to design engineering projects. A form, see Table 1, is provided to each SME to record this information. A section for comments, including reference to applicable section of the report is also provided. Finalized forms include resolution of comments from the author. Results from the SME reviews are recorded in Appendix B (Part I), Appendix C (Part II), and Appendix D (Part III) of the report.

SME:

SME Title:

Description of SME Experience:

Scope: *Review Part I of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution

Table 1. Subject Matter Expert Review Form

CHAPTER 4

RESULTS

The results of this case study are organized in three parts. Part one (4.1) provides a detailed work breakdown structure (WBS) of the most common activities that would take place during the design phase of an engineering design modification project (i.e., detailed design phase). Part two (4.2) provides a specific scope of work for a nuclear power plant design modification and describes activities to be completed as part of a conceptual design. Recommended person-hour estimates and activity durations are assigned. The third and last part (4.3) uses the Failure Modes and Effects (FMEA) tool to identify and analyze potential risks for each activity described in part two.

4.1. Part I: Work Breakdown Structure

Engineering design modification projects at nuclear power plants are a combination of activities that range from the design of an SSC up to implementation. Various resources are typically involved in the development of a project. Some of the dedicated resources are the project manager (i.e., the overall project lead who focuses on schedule and budget), the responsible engineer (i.e., the technical lead who serves as the primary point of contact for the development of the design), and resource engineers (i.e., task or discipline-specific engineers, also known as design team members by the SDP). Each project starts with the identification of an issue. This issue is then evaluated by plant personnel to determine if a physical change to the plant is required. Once the problem is evaluated, and a decision is made to make changes to the plant, a request is sent to the engineering department to initiate a plant design modification. This modification request eventually becomes an engineering project.

If the required resources are available, nuclear power utilities typically perform design modifications “in-house.” If these resources are not available, utilities reach out to external companies to perform the work. This case study is based on an engineering design modification developed for a hypothetical nuclear power plant by an external engineering company. The focus of this case study is the development of a clearly-defined example of an engineering design modification project from the perspective of a responsible engineer that is in the planning or estimating stage of the technical portion of a conceptual design.

The following is a list of activities that should be considered when developing the WBS for an engineering design modification project. This list is not comprehensive. Its primary purpose is to provide a basis for this case study. A formal process, such as the Standard Design Process (SDP) or a plant-specific design process should be followed to develop an accurate WBS for a realistic project. The WBS presented here includes activities to be performed as part of a detailed design change package (i.e., document). A portion of these activities is required to be completed as part of a conceptual design package. These activities are identified by placing an asterisk (*) next to each activity. Section 4.2 describes each of these activities. Section 4.2 also describes the differences between a detailed design and a conceptual design based on the SDP. A diagram of the WBS is presented in Figure 13 thru Figure 18.

- WBS.1. Engineering Design Modification
  - WBS.1.1. Define Project*
    - WBS.1.1.1. Obtain input from Customer and Project Manager
    - WBS.1.1.2. Problem Statement
    - WBS.1.1.3. Identify Resources Needed
    - WBS.1.1.4. Project Scope
      - WBS.1.1.3.1. Mechanical Engineering Scope
      - WBS.1.1.3.2. Electrical Engineering Scope
      - WBS.1.1.3.3. Civil/Structural Engineering Scope
      - WBS.1.1.3.4. Instrumentation and Controls (I&C)/Digital/Cyber Security Scope
    - WBS.1.1.5. Proposed Design Change/Problem Resolution
    - WBS.1.1.6. Design Inputs
  - WBS.1.2. Identify New and/or Update Affected Design Documents*
    - WBS.1.2.1. Obtain Input from Customer’s Design Engineering
    - WBS.1.2.2. Identify Affected Design Documents
    - WBS.1.2.3. Identify New Design Documents to be Generated
    - WBS.1.2.4. Drawings
      - WBS.1.2.4.1. Update/Generate Drawings
      - WBS.1.2.4.2. Review/Approval
      - WBS.1.2.4.3. Submit for Processing
    - WBS.1.2.5. Calculations
      - WBS.1.2.5.1. Update/Generate Calculations

  - WBS.1.2.5.2. Review/Verification/Approval
  - WBS.1.2.5.3. Submit for Processing
- WBS.1.2.6. Technical Reports
  - WBS.1.2.6.1. Update/Generate Technical Report
  - WBS.1.2.6.2. Review/Verification/Approval
  - WBS.1.2.6.3. Submit for Processing
- WBS.1.2.7. Specifications
  - WBS.1.2.7.1. Update/Generate Specifications
  - WBS.1.2.7.2. Review/Verification/Approval
  - WBS.1.2.7.3. Submit for Processing
- WBS.1.2.8. Procedures (e.g., plant operating procedures)
  - WBS.1.2.8.1. Update/Generate Administrative and Installation Procedures
  - WBS.1.2.8.2. Review/Verification/Approval
  - WBS.1.2.8.3. Submit for Processing
- WBS.1.2.9. Training Materials
  - WBS.1.2.9.1. Update/Generate Training Materials
  - WBS.1.2.9.2. Review/Verification/Approval
  - WBS.1.2.9.3. Submit for Processing
- WBS.1.2.10. Design Basis Documents
  - WBS.1.2.10.1. Update/Generate Design Basis Documents
  - WBS.1.2.10.2. Review/Verification/Approval
  - WBS.1.2.10.3. Submit for Processing

- WBS.1.2.11. Other Documents (e.g., data sheets, components lists, supplier documents)
    - WBS.1.2.11.1. Update/Generate Other Documents
    - WBS.1.2.11.2. Review/Verification/Approval
    - WBS.1.2.11.3. Submit for Processing

WBS.1.3. Installation Instructions*

- WBS.1.3.1. Obtain Input from Installing Group or Vendor
- WBS.1.3.2. Detailed Instructions
    - WBS.1.3.2.1. Obtain Input from Installing Group (i.e., constructability review)
    - WBS.1.3.2.2. Obtain Input from Supplier/Manufacturer
- WBS.1.3.3. Bill of Materials
    - WBS.1.3.3.1. Obtain Input from Customer (e.g., procurement, engineering, installing group)
    - WBS.1.3.3.2. Obtain Input from Supplier/Manufacturer
- WBS.1.3.4. Testing Instructions
    - WBS.1.3.4.1. Obtain Input from Customer (e.g., test group)
    - WBS.1.3.4.2. Obtain Input from Supplier/Manufacturer
- WBS.1.3.5. Submit for Implementation

WBS.1.4. 10 CFR 50.59/72.48 Review*

- WBS.1.4.1. Obtain Input from Licensing Group
- WBS.1.4.2. Safety Analysis Report (SAR) Impacts
    - WBS.1.4.2.1. Identify Recommended Changes to the SAR

WBS.1.4.2.2. Review/Approval

WBS.1.4.2.3. Submit for Processing

WBS.1.4.3. Technical Specification Impacts

WBS.1.4.3.1. Update Technical Specification

WBS.1.4.3.2. Review/Approval

WBS.1.4.3.3. Submit for Processing

WBS.1.4.4. Operating License Impacts

WBS.1.4.4.1. Identify Recommended Changes to the Operating License

WBS.1.4.4.2. Review/Approval

WBS.1.4.4.3. Submit for Processing

WBS.1.4.5. Submit to Licensing Group

WBS.1.5. Programs Impact*

WBS.1.5.1. Obtain Input from Program Owners and/or System Engineers

WBS.1.5.2. Cumulative Effects

WBS.1.5.3. Database Changes

WBS.1.5.4. Preventive Maintenance

WBS.1.5.5. Additional Information to Support Design

WBS.1.5.6. Other Site-Specific Requirements

WBS.1.5.7. Review/Approval

WBS.1.6. Project Activities

WBS.1.6.1. Design Package Inter-Discipline Review/Verification

WBS.1.6.1.1. Internal/SMEs*

WBS.1.6.1.2. Customer/SMEs

        - WBS.1.6.1.3. Professional Engineer
        - WBS.1.6.1.4. Human Performance/Risk
        - WBS.1.6.1.5. Verification
    - WBS.1.6.2. Meetings
        - WBS.1.6.2.1. Pre-Job Briefs*
        - WBS.1.6.2.2. Progress Updates
        - WBS.1.6.2.3. Technical/SME
        - WBS.1.6.2.4. Industry
        - WBS.1.6.2.5. Design Presentations*
    - WBS.1.6.3. Walkdowns*
        - WBS.1.6.3.1. Pre-Design
            - WBS.1.6.3.2.1. Obtain Input from Engineering
        - WBS.1.6.3.2. Post-Design/Constructability
            - WBS.1.6.3.2.2. Obtain Input from Implementing Group
    - WBS.1.6.4. Incorporate comments into design
    - WBS.1.6.5. Final signatures and approval
- WBS.2. Implementation Phase
    - WBS.2.1. Work Order Creation/Support
    - WBS.2.2. Minor Changes to Design due to Implementation
    - WBS.2.3. Performance Test Acceptance Report Reviews
    - WBS.2.4. Return SSC to Service
    - WBS.2.5. Installation Support
        - WBS.2.4.1. Outage

      - WBS.2.4.2. Non-Outage

- WBS.3. Close-Out/Completion Phase
  - WBS.3.1. Tracking of Document Completion
  - WBS.3.2. Additional Documentation
  - WBS.3.3. Final Reviews/Approvals

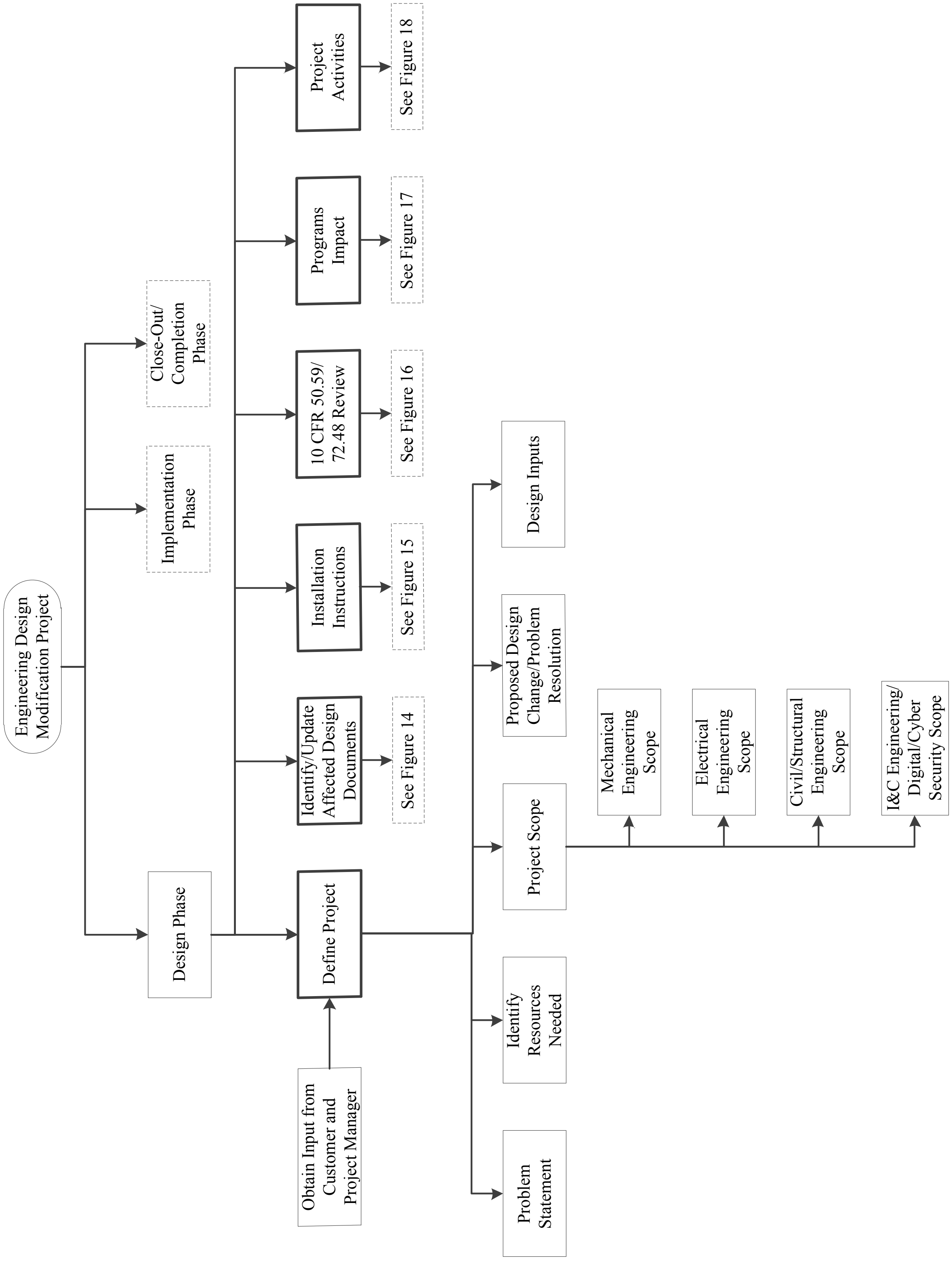

Figure 13. Work Breakdown Structure Diagram – Overall

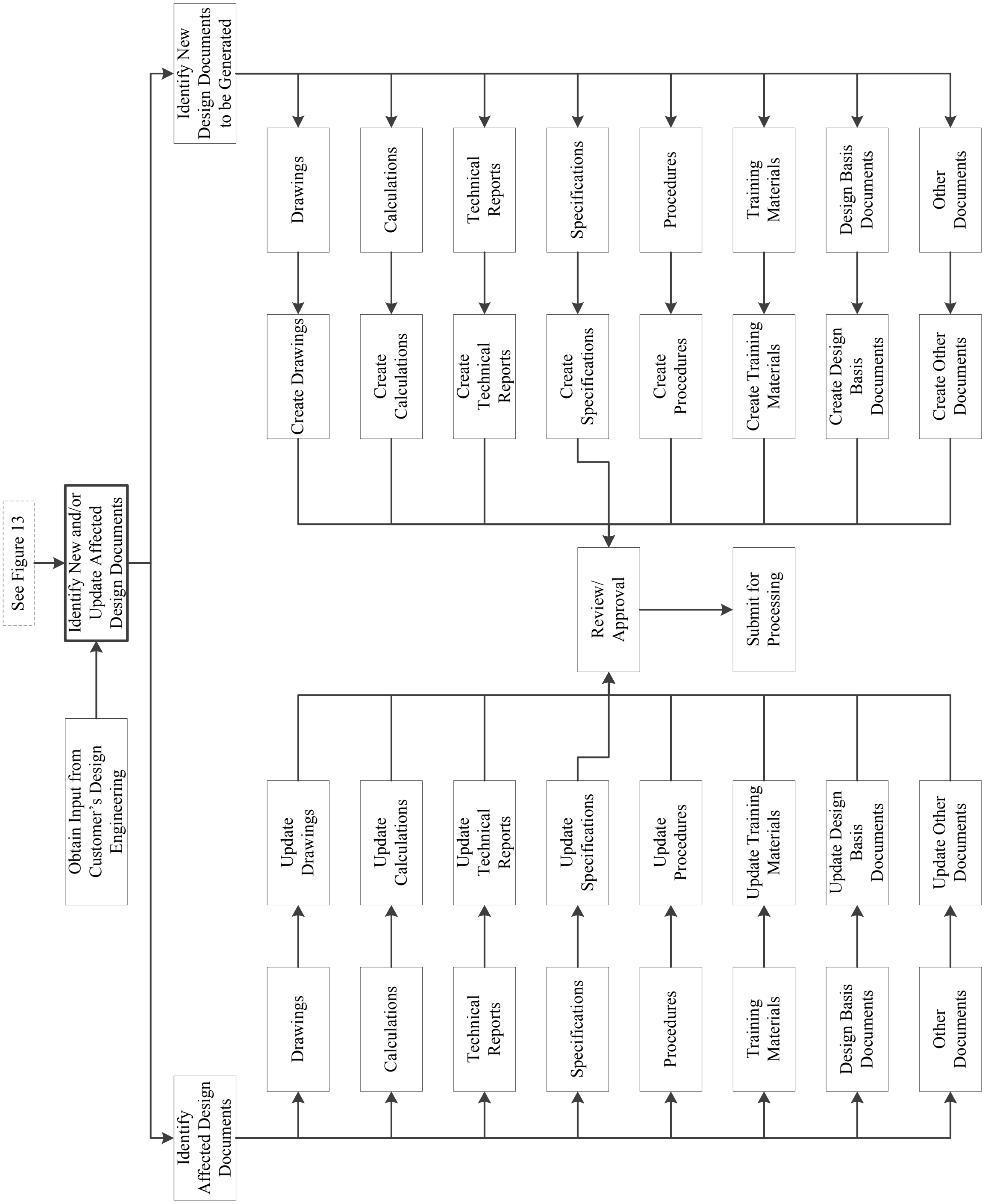

Figure 14. Work Breakdown Structure Diagram – Identify New and/or Update Affected Design Documents

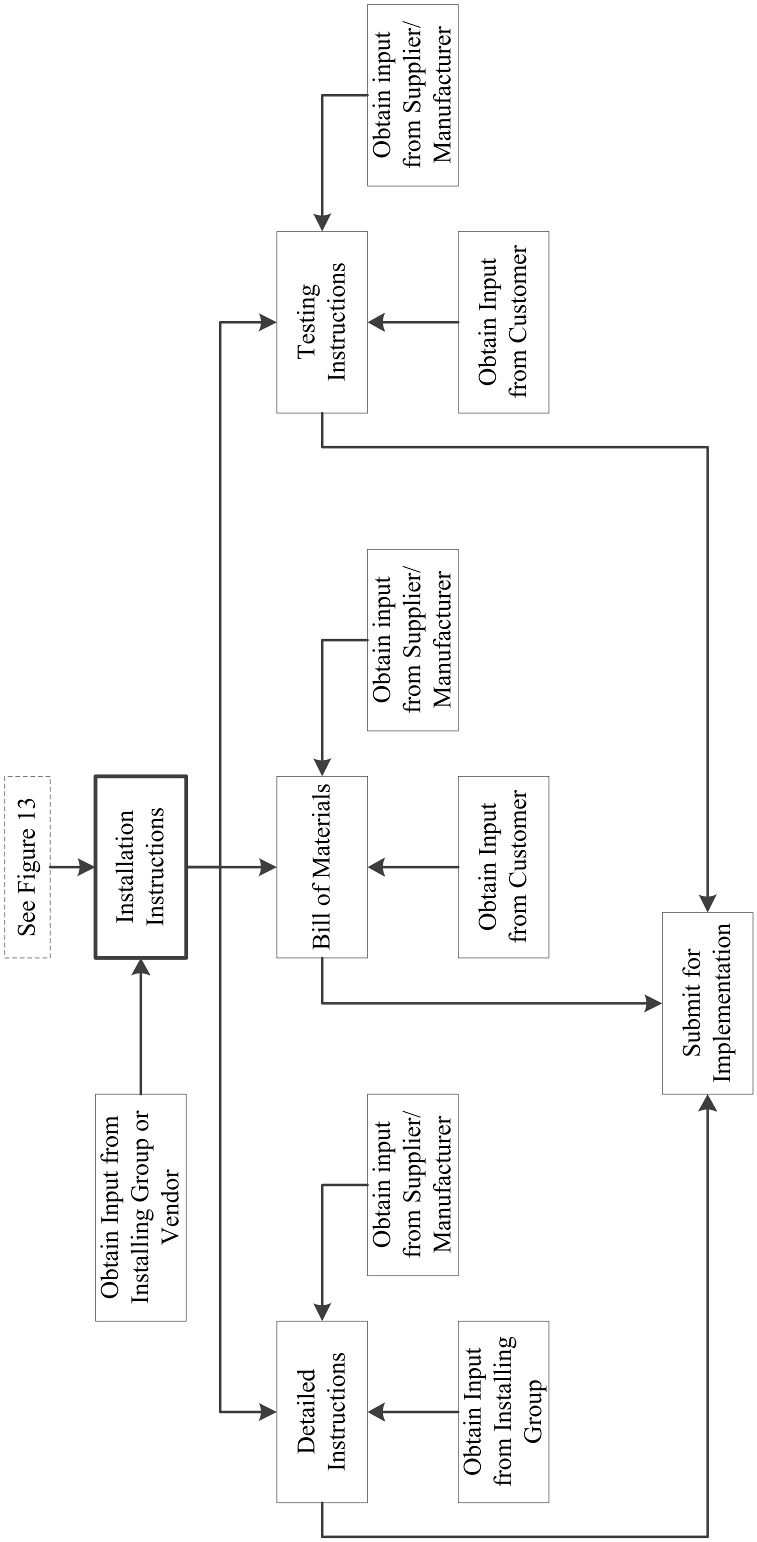

Figure 15. Work Breakdown Structure Diagram – Installation Instructions

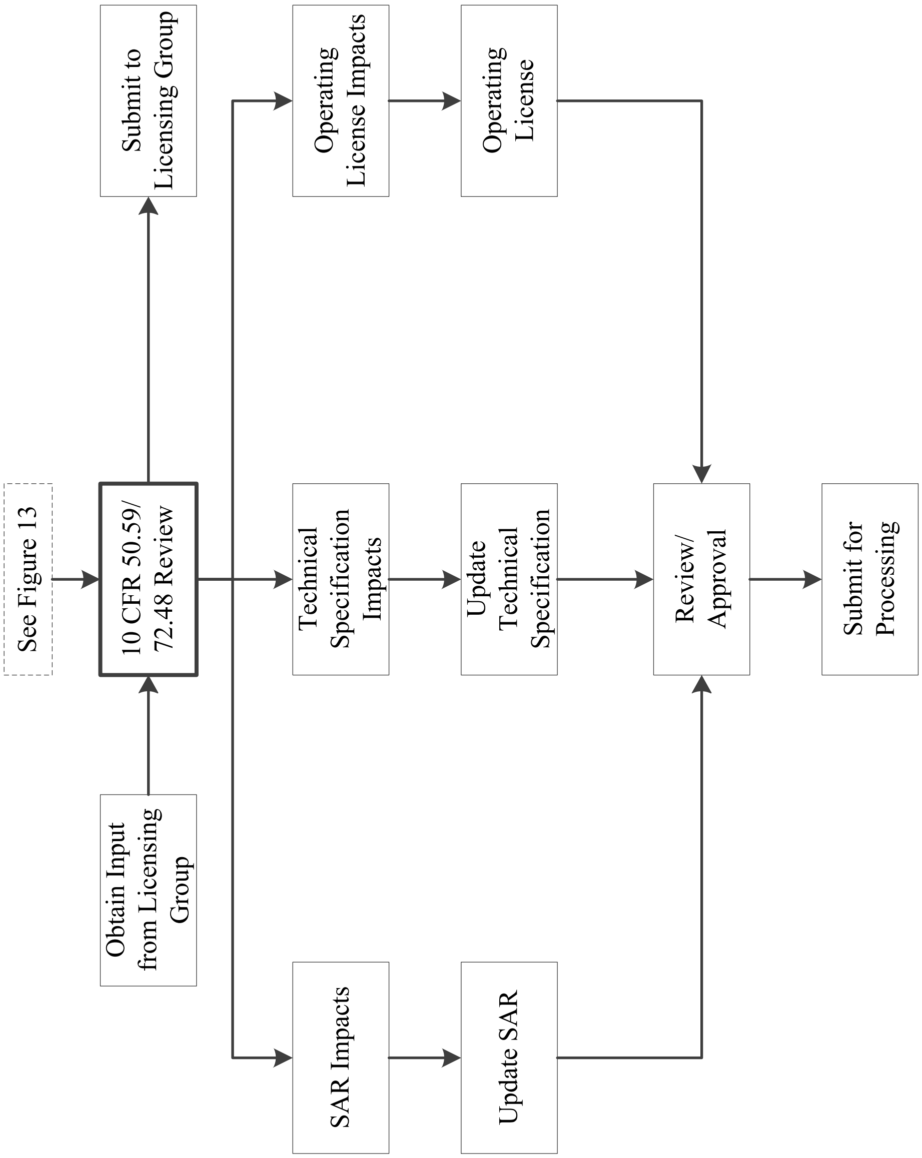

Figure 16. Work Breakdown Structure Diagram – 10 CFR 50.59/72.48 Review

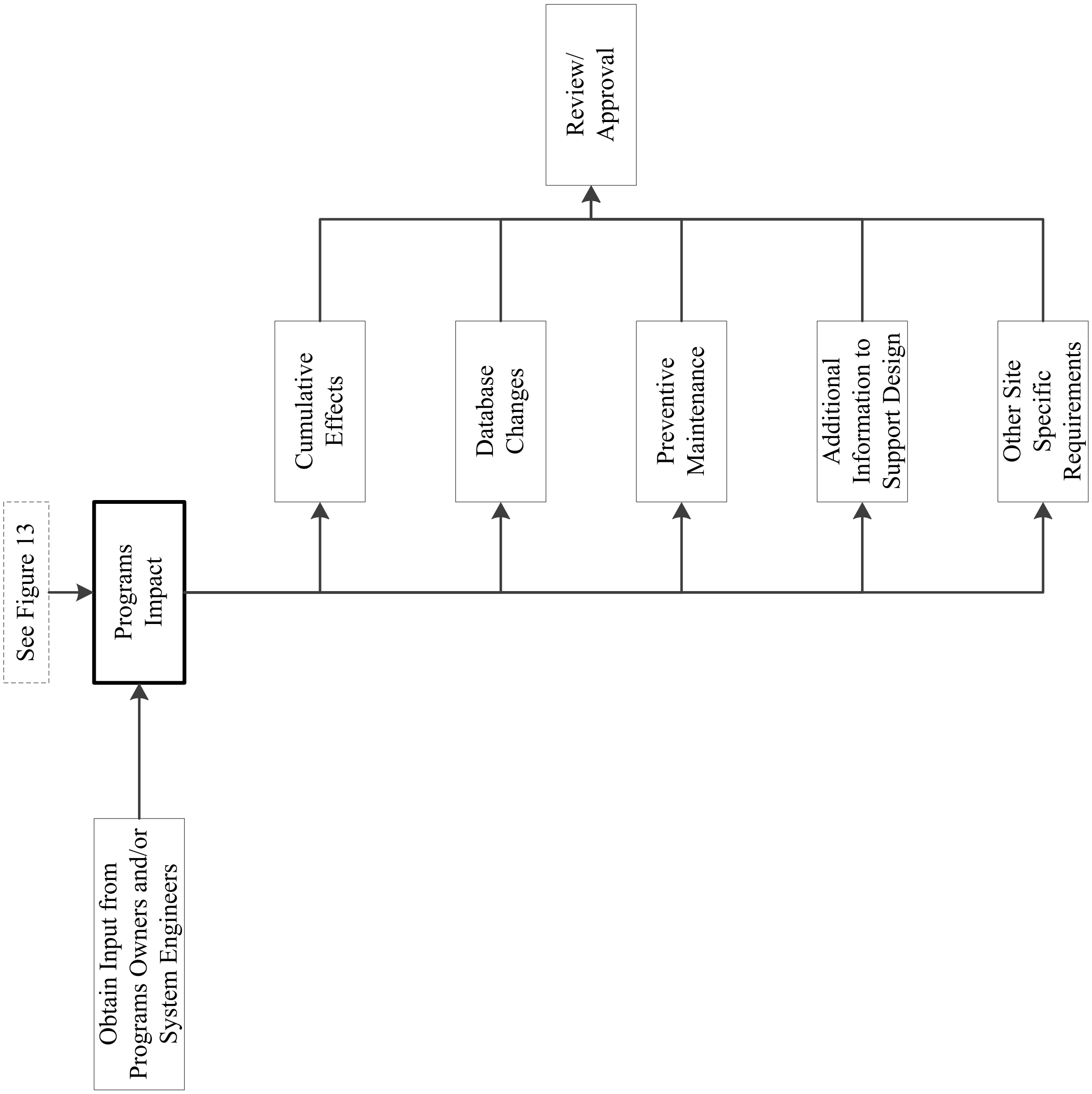

Figure 17. Work Breakdown Structure Diagram – Programs Impact

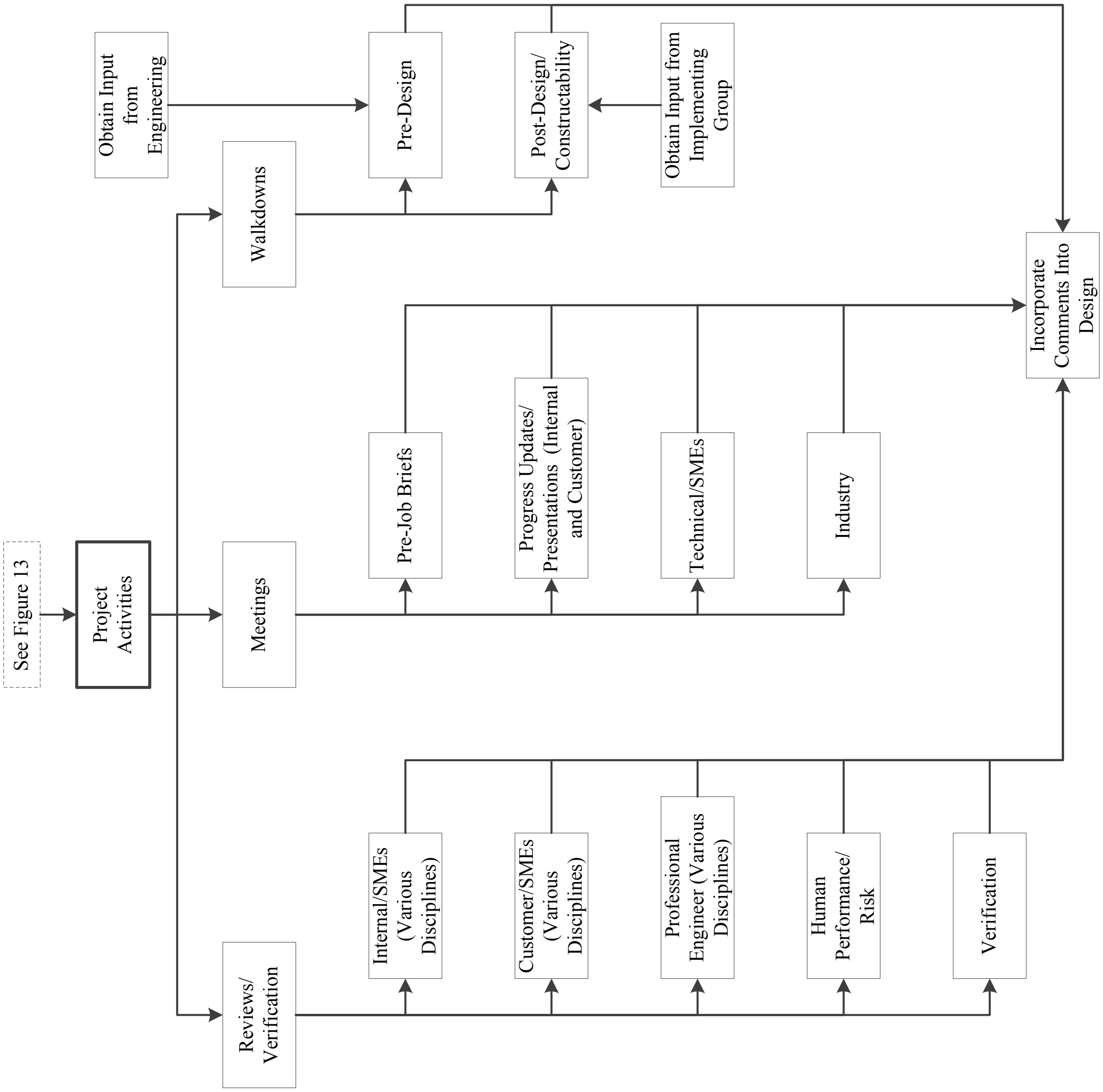

Figure 18. Work Breakdown Structure Diagram – Project Activities

4.2. Part II: Activity Definitions and Estimates

The scope of an engineering design project, especially for a plant modification, can be extensive, as shown in the WBS in Section 4.1. Therefore, projects are typically divided into phases. The Standard Design Process (SDP; SDPSC, 2017), shown in Figure 19, identifies six major design phases: initial scoping phase, conceptual/common design phase, detailed design phase, planning phase, installation/testing phase, and design closure phase. The case study presented here focuses on the SDP conceptual design phase (i.e., ~30% of the design (SDPSC, 2017)) shown in Figure 20.

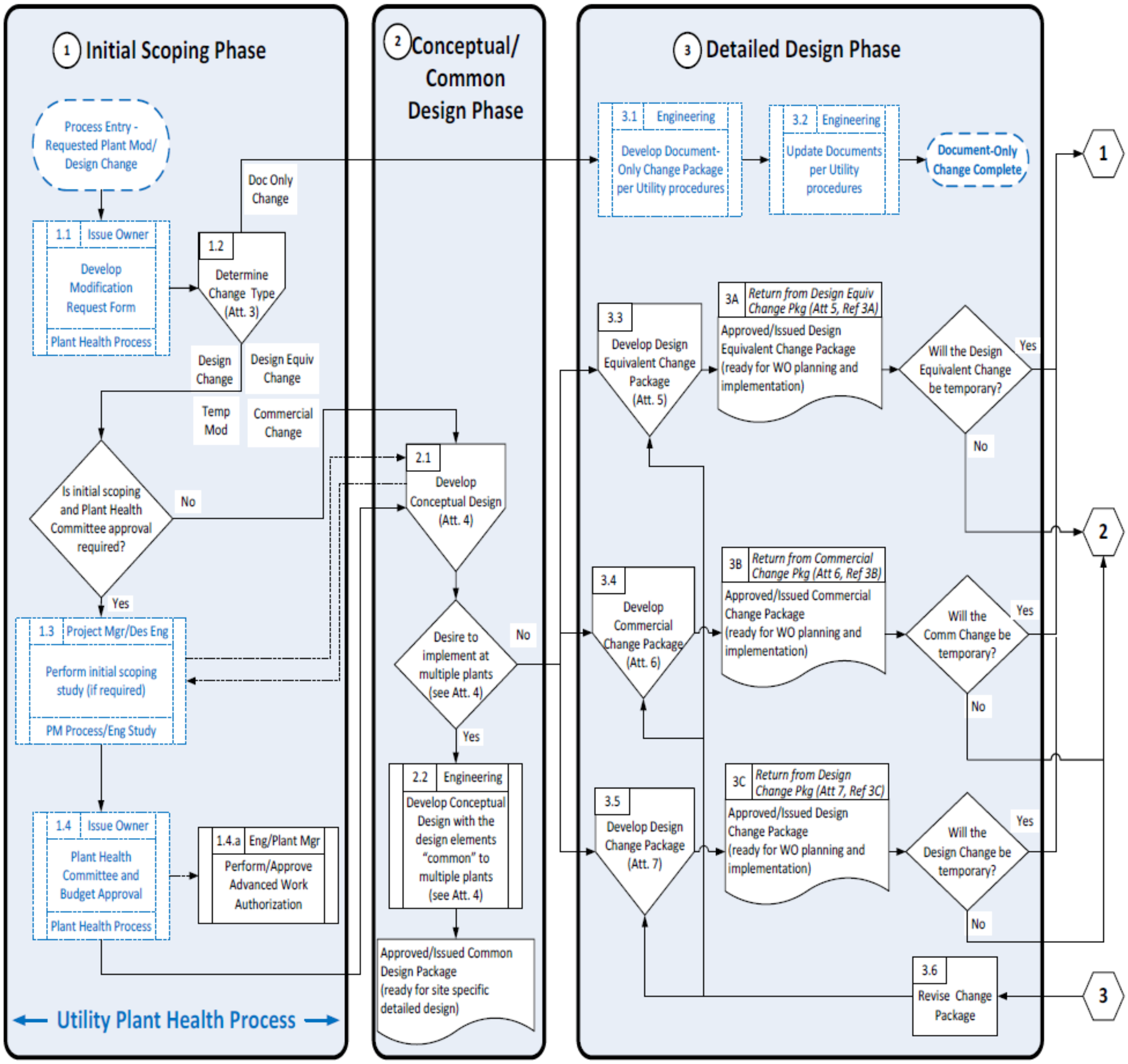

Figure 19. Standard Design Process Flowchart (SDPRC, 2017)

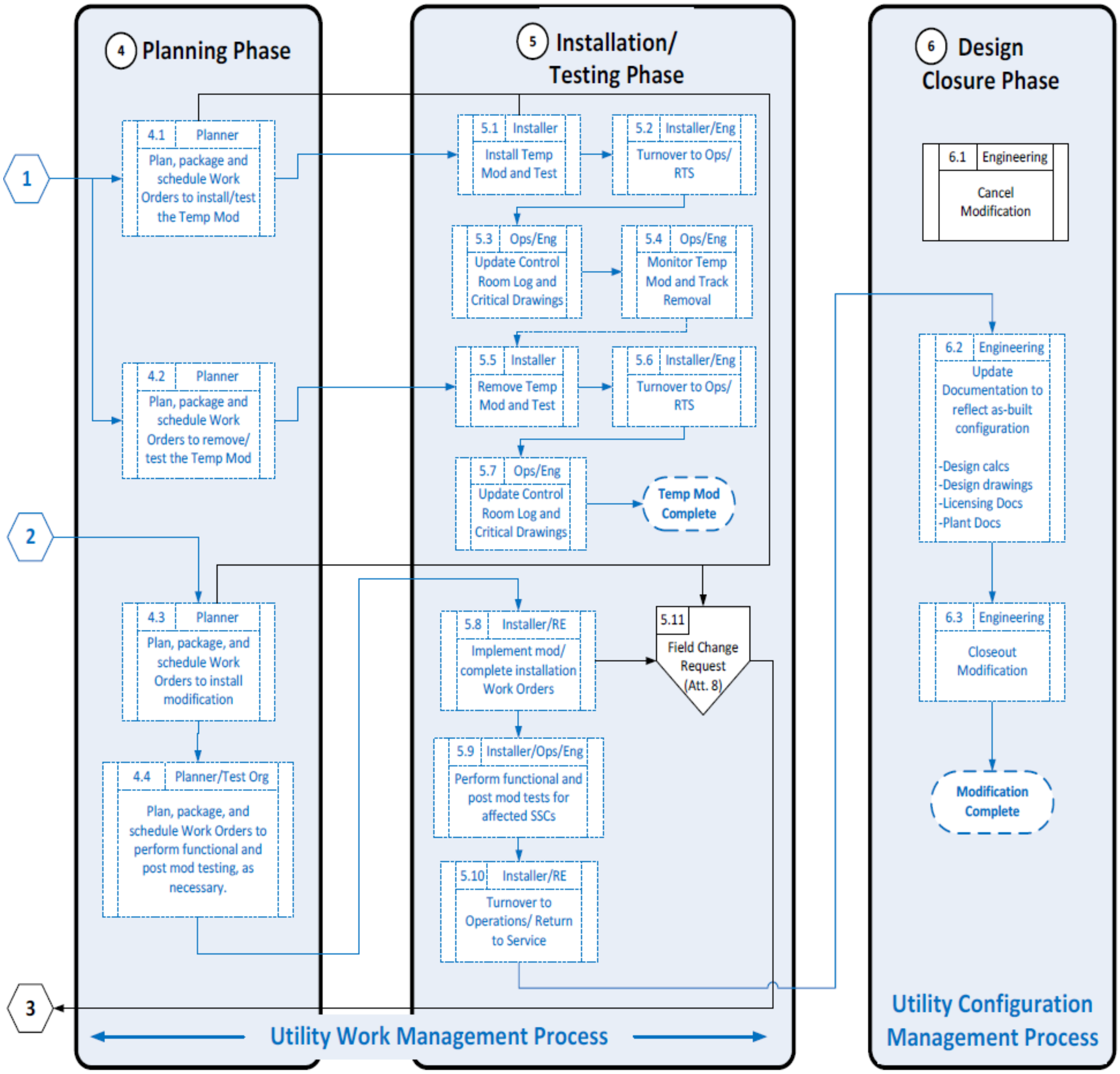

Figure 19. Continued

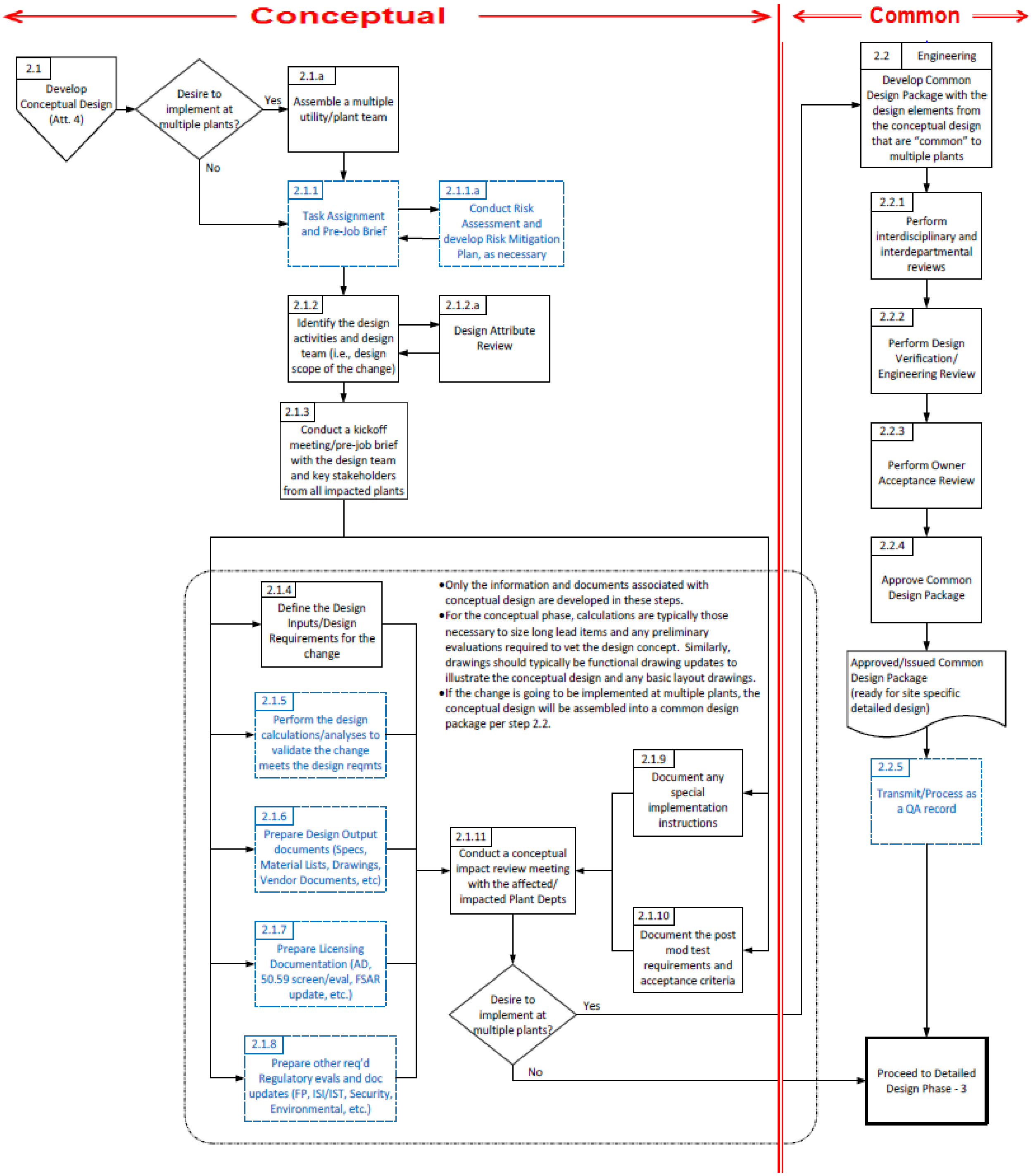

Figure 20. Conceptual/Common Design Phase Flowchart (SDPRC, 2017)

By the time a project is assigned to a responsible engineer, especially one external to the plant, the initial scoping phase has already been completed by plant personnel. The next phase is the conceptual/common design phase. The common design phase applies to nuclear fleet-level designs and evaluations (SDPSC, 2017) and will not be discussed since this case study is based on a single unit plant.

Per the SDP (SDPSC, 2017), a conceptual design includes the following major elements:

1. Identification of the design scope,
2. Identification of team members,
3. Development of the preliminary design inputs, requirements, and deliverables.

During the conceptual design phase, the entire project structure can be delineated with more accuracy; therefore, estimates for future phases can be refined. There is a risk of over-estimating or under-estimating a project from beginning to end. Because of this, a phased approach is preferable.

This case study describes a simplified WBS for a hypothetical project scope. It also develops project estimates and schedules for a design modification performed for a hypothetical nuclear power plant named Nuclear Plant 1. The purpose of this modification is to add a means to use filtered water from the Filtered Water Tank (FWT) for alternative or emergency purposes. The project focuses on the following overall scope:

- Install a 6” drain line and valve to the FWT discharge line at Nuclear Plant 1, a single unit plant. The FWT is a non-nuclear safety related (NNS) tank containing filtered water.
- The new line is classified as NNS.

- One P&ID is required to be updated. This P&ID is also a figure on the plant's Safety Analysis Report (SAR).
- One pipe support is needed to support the new line.
- No wall penetrations are required.
- The responsible engineer for the project will be a mechanical engineer.
- One (1) civil/structural resource engineer will be involved in the project.
- The conceptual design shall be completed in 12 weeks.
- Project weeks are 40-hour weeks, five (5) days per week, and seven (7) hours each day (i.e., approximately 87% utilization).
- 25% of the total allotted time will be assigned to the resource engineer.

The descriptions of each activity and person-hour estimates to complete the activities are discussed. As stated previously, this case study will focus on activity descriptions and person-hour estimates for the development of a conceptual design.

4.2.1. Pre-Job Brief

As defined by Davenport (2005), knowledge workers have high degrees of expertise, education, or experience, and the primary purpose of their jobs involves the creation, distribution, or application of knowledge. The Institute of Nuclear Power Operations (INPO) classifies engineers as knowledge workers. In the 05-002 report, INPO provides a list of tools that can be applied to anticipate, prevent, and catch in-process errors (INPO, 2005). All of these tools are important to developing a high-quality product and should be applied throughout the life of a project. The pre-job briefing tool is an essential tool to apply at the beginning of any project and is discussed here.

A pre-job brief is a discussion held by the responsible engineer and their responsible supervisor to (INPO, 2005):

1. To ensure the engineer is qualified to perform the assigned task,
2. To prepare the engineer for what to accomplish, and
3. To sensitize the engineer to what to avoid and to identify and compensate for error-likely situations that could lead to the product jeopardizing the plant or person.

The pre-job brief is the first step to ensure a project is being developed the right way from the beginning. Always ensure your direct supervisor organizes or schedules a pre-job brief before the start of any activity such as planning and estimating the effort to develop a conceptual design package. Pre-job briefs should be used every time an activity is started and can be led by responsible supervisors, project managers, and responsible engineers alike. A pre-job brief is a tool that can also be used to reduce activity risks as shown in the risk analysis performed in Section 4.3.

4.2.2. Procedure Use and Adherence

The next step on any project, especially a nuclear plant modification project, is to identify applicable procedures or documents, and their latest revisions or versions. The controlled (i.e., revision or version approved for use) documents can be found in the plant's controlled document repository. As a good practice, never rely on printed procedures or documents that have been saved on local folders or personal computer desktops. These are not controlled and can contain old information. During the life of a project controlled documents may change, or not change at all. Always ensure that the latest procedures and forms are being used or submitted with project deliverables and that the latest versions of documents are being used for updates. Failing to do so may cause schedule or operability issues. The same concept applies to training and qualifications. Management and individual project contributors should always ensure that training and qualifications are current before assigning or starting work.

4.2.3. Project Definition and Pre-Design Walkdown

The first deliverable on any project should be to define the project scope. The overall scope of the project is defined in the initial scoping phase. During the development of the conceptual design phase, the scope is expanded to include technical details. The definition of the scope should always start with a walkdown and discussions with customer key stakeholders to understand the entire assignment, especially to outline the technical information.

Pre-design walkdowns are essential to define a project and to develop a design. The purpose of this walkdown is to get familiar with the system or component that needs to be modified and to give the engineer a sense of the magnitude of the work. Walkdowns are also used to confirm information, especially from drawings. Even if a drawing is approved for use, it does not mean that it contains accurate or complete information, especially for non-safety related systems, since more focus is put on safety-related systems. Walkdowns are excellent tools to confirm this information and to guarantee that the design is based on correct, not assumed data.

Plant or customer key stakeholders are project managers, engineers, or plant operations and maintenance personnel familiar with the issue. Interviewing plant operations and maintenance personnel can be beneficial to a project since these are the individuals interacting with the systems every day. They typically understand how these systems and components work, can identify the real issues they face, and can also provide feedback on realistic solutions to the problems. System and component engineers are another excellent source of information. These engineers are in charge of the health of systems and major plant components and often perform monitoring activities which can provide the backup data to support possible resolutions. Design engineers, on the other hand, know how these issues relate to the plant's design basis. Design engineers are vital resources when identifying and updating impacted documents. All the resources previously described can also assist in developing the background of the issue.

The definition of a project typically consists of the problem statement (i.e., what?), background description (i.e., why?), and overall resolution of the problem (i.e., how?). This definition should be a comprehensive description of the issue, the reason why it needs to be solved, and how will it be solved. The background should also include reference to regulatory requirements, system health issues, maintenance issues, or inspection findings that initiated the change. The safety classification (i.e., non-nuclear safety related, safety-related, or quality/augmented quality) of the project, or system/component, should also be described. The project's safety classification will give the reader or reviewer a sense of how complex the project is. Non-nuclear safety-related projects are typically the less complex, while safety-related projects are the most complex due to the amount of documentation and evaluations that need to be performed to maintain the safety classification.

To assist reviewers, a detailed description of each engineering discipline's (e.g., mechanical engineering, electrical engineering, civil/structural engineering, and I&C engineering) scope should also be incorporated. This section is typically completed by the responsible engineer but should include input from resource engineers. In the case of our simplified case study, this section can be described as follows:

- Mechanical Scope – Install a 6” drain line to the exiting FWT 8” spare drain nozzle. A 6” gate valve and s threaded cap will also be installed. The line will be 2’ in length and will not require pipe stress analysis performed.
- Electrical Scope – None. For the purposes of this simplified case, it will be assumed that there are no electrical controls and no heat tracing required.
- Civil/Structural scope – One (1) pipe support shall be installed on the new 6” drain line.
- I&C Scope – None.

The definition of a project is an essential part of any design change. This section may also change during the life of the project; therefore, it should be revisited during every phase. The scope also helps the responsible engineer and project manager on the identification of a project team. In our case study, and for technical effort estimation purposes, the only resource engineer involved will be a civil/structural engineer. For the remainder of this case study, all activity person-hour estimates will be provided for the responsible engineer, who is also the mechanical resource engineer, and a civil/structural engineer. In some cases, the responsible engineer might not be a resource engineer. Therefore, person-hour estimates should consider that. For efficiency purposes, it is preferred that the responsible engineer works in the discipline of the most scope. For example, if most of the scope is mechanical, then it is preferred for the responsible engineer to be a mechanical engineer. For simplicity, engineering supervision, project management, and other overhead charges will be ignored when developing the estimate. These charges are typically percentages of the direct engineering cost.

Since the overall scope of a plant modification is mainly developed during the initial scoping phase, the effort to develop the technical portion is based on discussions held with plant personnel, walkdowns, and research of documents. A 20 person-hour estimate for defining the project and 60 person-hours for walkdowns will be allocated. In realistic terms, 20 hours would be enough to visit the site for a day, interview personnel, and type the information gathered. The 60-hour allocation for walkdowns will be used throughout the development of the conceptual design, up until delivery of the package. Assuming 8 hour days, this translates to 7 to 8 days' worth of walkdowns. The assistance of the resource engineer is also required, which would be a portion of the hours assigned to the responsible engineer. In this case, approximately 25% of the time would be assigned for project definition and walkdowns, which translates to 5 hours and 15 hours respectively. The estimates for person-hours and activity duration are shown in Table 2.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Define Project	20	5	1 week
Walkdowns	60	15	11 weeks

Table 2. Estimate for Project Definition and Walkdowns

4.2.4. Design Inputs

Design inputs are defined by the American Society of Mechanical Engineers (ASME) as the criteria, parameters, bases or other design requirements upon which detailed final design is based (ASME, 1974). In other words, the design inputs are the researched information that will be used to develop the design. The SDP procedure (i.e., IP-ENG-001), Attachment 10, provides a guide to follow when evaluating design inputs. Nuclear power plants, as part of a design process, might also have specific procedures in place that describe the process of gathering or identifying design inputs. These procedures also serve as guides on what parameters to consider and what forms or documents need to be completed. Some processes, such as the SDP, are industry-wide and provide a standard guide that any plant can apply.

The SDP procedure provides a comprehensive list of thirty-three (33) design input considerations. Some of these include:

- Design conditions (e.g., pressure and temperature),
- Codes and standards (e.g., ASME, Institute of Electrical Engineers and Electronics (IEEE), American Welding Association (AWS), American Concrete Institute (ACI)), and
- Requirements (i.e., performance, materials, interface, loading, layout, operability, redundancy, security, safety, failure, etc.).

The design inputs document for a plant modification is not a “once and done” document or process. The design inputs document is a “living” document that will most likely be updated during every phase of the project. Therefore, person-hour estimates should be allocated to this activity at every phase of the project.

Since most of the research for a design occurs during the conceptual design phase, this phase should include the biggest effort regarding person-hours to develop design inputs. By the time the conceptual design is completed most of the design inputs should be identified and confirmed by the customer. Further changes to design inputs occur due to scope changes or interface changes that occur throughout the development of the design. Given that this case study is based on a 12-week milestone with 11 weeks assigned to developing design inputs and assuming half of the engineer's time will be spent in research, at least 120 hours should be assigned to this effort. Again, 25% of that time will be assigned to the resource engineer. The estimates for person-hours and activity duration are shown in Table 3.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Design Inputs	90	30	11 weeks

Table 3. Estimate for Design Inputs

4.2.5. Identify New and/or Update Affected Design Documents

Permanent modifications to nuclear power plants typically result in changes to the plant's design basis. Documents need to be created or updated to reflect the physical changes made to the plant and to maintain the plant's design basis current. Some of the documents that could be created or modified are drawings, calculations, technical reports, specifications, procedures, training materials, and design basis documents, among others. The identification, evaluation, and initial updates to these documents can be used to define the scope of subsequent design phases, such as the detailed design phase. The following sections describe the scope and processes of updating these documents.

4.2.6. Drawings

Drawings are graphical representations of the plant's configuration or design. Based on the scope of the hypothetical project used in this case study the scope of this portion would be:

1. Update the existing P&ID that currently shows the tank with a spare nozzle.
2. Create a new isometric drawing showing the new piping configuration.
3. Update existing FWT drawings, most likely a vendor drawing, to either add the new piping or reference the new isometric drawing.
4. Update equipment drawings that potentially show the tanks spare nozzle.
5. Update any other drawings that use the P&ID as a base. Some of these could be safe shutdown drawings or pipe stress analysis drawings.
6. Create a new drawing to show the design of the new pipe support.

The creation of a new isometric drawing will aid the engineer in the design and constructability of the piping. Since this is a new drawing, it should be developed in some Computer Aided Design (CAD) software such as AutoCAD or SolidWorks, among others. Depending on the complexity of the design the support of a design technician could be needed for this activity. For this case study, it is assumed that the principal and resource engineers are both trained and skilled in CAD software and will be performing the drafting task. Having engineers trained in the use of CAD software can save time and money in a project since it removes one resource and allows the design to rely on the technical expert.

The update of existing drawings could be more complicated than creating new drawings. Depending on the agreements reached with the customer updated drawings might consist of markups of PDF (i.e., portable document format) type documents or updates to CAD drawings. During the conceptual design phase it is essential to identify the following:

1. Are impacted drawings available in CAD? What format or software?
2. If drawings are available in CAD format, would the customer prefer the engineering company to update these or does the customer have the responsibility to update them?
3. If drawings are not available in CAD format, are markups of PDF documents acceptable to the customer? What information should those drawing markups include?

The answers to these questions should be used as input when developing the subsequent phases of the project. For a conceptual design, PDF copies of identified impacted drawings should be obtained from the customer. Markups of these PDF documents should be included as part of conceptual design package to serve as a demonstration of the conceptual design. Formal updates to drawings should occur after the conceptual design is complete and accepted by the customer.

For the purpose of person-hour allocation, for the hypothetical scope, 40 hours will be assigned to the development of a new piping isometric drawing, and 20 hours will be assigned to the development of a new pipe support drawing. It will be assumed that four (4) additional impacted drawings will need to be marked up. A total of 2 hours will be assigned to each drawing. Regarding resources, the responsible engineer is in charge of creating the isometric drawing and marking up impacted drawings. The resource engineer is responsible for creating the new pipe support drawing. Peer reviews of each drawing will also need to be performed. Peer reviews of each drawing are also needed at this stage. Peer reviewers provide a defense to detect errors and defects before the completion of documents by reading and checking the quality of another’s work product (INPO, 2005). At least 1 hour should be allocated for peer reviews. For this case study, a total of 6 hours will be allocated for drawing peer reviews. This activity will be performed by additional resources, preferably one mechanical engineer for the mechanical drawing and one civil/structural engineer for the civil/structural drawings. The estimates for person-hours and activity duration are shown in Table 4.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
New Drawings	40	20	2 weeks
Impacted Drawings	8	0	1 week
Drawing Peer Review	0	0	1 week

Table 4. Estimate for Drawings and Peer Reviews

Activity	Person-Hour		Duration
	SME (mechanical)	SME (civil/structural)	
New Drawings	0	0	2 weeks
Impacted Drawings	0	0	1 week
Drawing Peer Review	5	1	1 week

Table 4. Continued

4.2.7. Calculations

Calculations are mathematical representations performed to show the results of an analysis. Each nuclear power plant should have procedures that describe the process utilized when performing calculations. In this case study, we can assume that two (2) calculations will be needed, a hydraulic calculation and a pipe support calculation.

The hydraulic calculation determines the performance parameters of the new FWT drain line. This calculation should demonstrate the total flow of water that could be achieved through the new line. In the case where a line size is not provided as part of the overall scope of the project and a total required flow is provided instead, this calculation would be used to determine the size of the pipe required to fulfill the performance requirement. The pipe support calculation determines the allowable loads for the designed support. This calculation also determines the appropriate sizes of all individual members. Since these calculations will be performed under the conceptual design phase, they will be considered preliminary calculations. Formal calculations are completed in later design phases. The hydraulic calculation will be performed by a mechanical engineer (or responsible engineer). The pipe support calculation will be performed by a civil/structural engineer (or resource engineer). A peer review should also be conducted of each calculation to ensure that the methods, assumptions, and results of the calculation are correct. A total of 40 hours can be assigned to the development of each preliminary calculation. Half of this total time, 20 hours, can be assigned to the peer review of the calculation. Assuming the engineers will not be dedicated full time to this activity, a total of 2 weeks can be assigned to the performance of these calculations, and one week can be designated for the peer review. The estimates for person-hours and activity duration are shown in Table 5.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Calculations	80	0	2 weeks
Calculation Peer Review	0	0	1 week

Table 5. Estimate for Calculations

Activity	Person-Hour		Duration
	SME (mechanical)	SME (civil/structural)	
Calculations	0	0	2 weeks
Calculation Peer Review	40	0	1 week

Table 5. Continued

4.2.8. Technical Reports

Technical reports are typically created to record engineering analyses or engineering positions on a specific topic. Since the scope of this modification is simple and only adds a drain line to FWT, no particular analyses or engineering positions are created from it. Therefore, for this case study, it is assumed that no technical reports are created nor impacted by this engineering change.

4.2.9. Specifications

Specifications are documents that record detailed requirements or characteristics of a system, structure, or component. Specifications can be of different types such as design, procurement, fabrication, or material, among others. As an example, a procurement specification would be required to purchase a safety-related valve to be installed in a radioactive controlled area. This specification will include details in size, material, and performance requirements. For this case study, since the new line is designated as non-nuclear safety related, the valve to be installed will not have any “nuclear” specific requirements and will more than likely be an “off the shelf” or “commercial grade” item. Therefore, no specification will be required. Details on the valve, such as material and size, would be included in procurement documents. Some of these documents could be requests for quotes or purchase orders.

4.2.10. Plant Operating Procedures

Procedures have for various purposes at nuclear power plants. Some procedures are used for administrative purposes and only include descriptions of processes. Plant operating procedures are used to perform work in the field. Typically nuclear power plants have designated groups or departments that are responsible for updating plant operating procedures.

There are two (2) approaches to identify impacted procedures. One approach is for the responsible engineer or resource engineers to identify the procedures by performing research. Another method is to allow stakeholders or reviewers to identify impacted procedures within their field of work during design package reviews. The second approach is the most efficient since it will enable subject matter experts to identify the procedures and the appropriate impact.

For this case study, it is assumed that at the time the project estimate is performed there was no knowledge of impacted procedures. Therefore, hours should be allocated for the responsible and resource engineers to perform research during the conceptual design phase to identify the impacted procedures. At least 20 hours should be assigned to the responsible engineer and 10 hours to the resource engineer to perform this task, with a one (1) week time duration. The estimates for person-hours and activity duration are shown in Table 6.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Identification of Impacted Procedures	20	10	1 week

Table 6. Estimate for Procedures

4.2.11. Training Materials

Training materials are typically those used to train nuclear power operators on the maneuver of new systems or components. As with procedures, these training materials are identified by stakeholders from the plant's training department during design package reviews at later design phases. Therefore, for this case study, no hours will be allocated to the identification or update of training materials.

4.2.12. Design Basis Documents

Design basis documents, or DBDs, are plant-specific documents that describe the high-level functional requirements, interfaces, and expectations of a facility, structure, system or component that are based on regulatory requirements or facility analyses (SDPSC, 2017). These documents are an overall description and refer to other specific design documents such as calculations and technical reports. DBDs are an excellent source of information on a particular system and typically describe all the aspects of that system. Therefore, a scope such as the one presented in this case study will impact a DBD. It is more than likely that the FWT, being a major component or structure at a plant will be described on a DBD. The specific DBD will differ from plant to plant. Specific changes to the DBD will also depend on how much detail the plant includes in these documents. For this case study, hours should be allocated to identify impacted DBDs (more than one could be impacted depending on how systems are set up) and to detect potential changes to the DBD. Both the responsible and resource engineers will be performing this activity. A total of at least 20 hours should be allocated to the responsible engineer and 10 hours to the resource engineer. Time allotted should be around one week. The estimates for person-hours and activity duration are shown in Table 7.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Design Basis Documents	20	10	1 week

Table 7. Estimate for Design Basis Documents

4.2.13. Installation Instructions

Even though the SDP does not consider detailed installation or testing instructions as being part of the conceptual design phase, it is a good practice to start thinking about how the design change will be implemented and tested, especially based on the phases of implementation. This information can be added to plant specific forms or design package sections, or even to the project scope if needed.

During the conceptual design phase, some important information to add is the materials needed to implement the change. This list or bill of materials does not need to be detailed in this phase. The list should provide reviewers an idea of the major equipment to be installed or procurement long-lead components. For this case study, essential items to list are:

1. Pipe size, length, and material
2. Valve types, including vendor and models if available
3. Pipe support elements and construction materials, and
4. Fittings (e.g., flanges, gaskets, elbows, pipe caps).

If available at this stage, adding references to plant stock numbers is also helpful.

The materials needed for the design will be identified as the design is developed, preferably after drawings are complete. Because of this, the duration of this activity should be the duration of the project from the development of drawings to completion of conceptual design phase (i.e., 8 weeks). For this case study, a total of 20 hours can be allocated to the responsible engineer and 20 hours to the resource engineer. Both engineers, in this case, will be developing a separate design, which is piping and pipe support. The estimates for person-hours and activity duration are shown in Table 8.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Bill of Materials	20	20	8 weeks

Table 8. Estimate for Bill of Materials

4.2.14. 10 CFR 50.59/72.48 Review

The Nuclear Regulatory Commission's Chapter 10 (i.e., nuclear) of the code of federal regulation (i.e., CFR), part 50.59, titled "Changes, Tests, and Experiments," describes the conditions by which a licensed nuclear power plant can make changes in the facility as described in the final safety analysis report (as updated), make changes in the procedures as described in the final safety analysis report (as updated), and conduct tests or experiments not described in the final safety analysis report (as updated) without obtaining a license amendment (NRC, 2017) . The NRC's 10 CFR 72.48, titled "Changes, tests, and experiments," describes the conditions by which a licensee or certificate holder may make changes in the facility or spent fuel storage cask design as described in the Safety Analysis Report (SAR) (as updated), make changes in the procedures as described in the SAR (as updated), and conduct tests or experiments not described in the final safety analysis report (as updated), without obtaining a license amendment or a Certificate of Compliance amendment submitted by the certificate holder. In other words, the 50.59 and 72.48 reviews are licensing reviews performed to ensure that the changes being made to the plant are either covered under the current license or need further review by the NRC. For the case study presented here, only the 50.59 applies since the design changes to be performed only impact plant systems and do not impact the spent fuel storage cask.

Power plants have specific procedures that need to be followed to perform these reviews. The process is typically composed of three major parts. The first process is the applicability determination (AD) which is the method for determining the appropriate regulatory processes and reviews that are required for a proposed activity in accordance with utility-specific procedures (SDPSC, 2017). The second process is the screening which determines if the proposed change or activities have an adverse effect on SAR described safety functions. The third, and last, process is the evaluation which determines if the proposed change or activity needs approval from the NRC. Another licensing action that could be required is the update of the Safety Analysis Report (SAR).

The SAR, or FSAR (i.e., Final Safety Analysis Report) as sometimes also called, is a plant-specific document that shall include information that describes the facility, presents the design bases and the limits on its operation, and presents a safety analysis of the structures, systems, and components and of the facility as a whole (NRC, 2017). This document includes information such as plant-specific location, results of environmental and meteorological programs, descriptions and analyses of SSCs, kinds, and quantities of radioactive materials, and facility operation, which includes organizational structure, the conduct of operations, and plans for coping with emergencies, among others. Regarding systems, for small scopes as the one presented in this case study, the descriptions provided in the SAR typically do not require change. However, figures may require changes. In this case study, a P&ID which is also a SAR figure is being updated. This change automatically warrants an amendment to the SAR which is a separate process from the 50.59/72.48 and should be accounted for as an independent activity within the project.

During the conceptual design phase, per the SDP, preliminary or draft licensing documents should be prepared. The AD is a document that is always required. The screen is required if the AD determines it is. The same way, the evaluation is required if the screen determines it is. Based on the scope provided for this case study, it is likely that only an AD will be required. Also, since it was already identified that the impacted P&ID is also a SAR figure, changes to the SAR will be required. Since the 50.59/72.48 review will require extensive research of licensing documents (i.e., SAR, Technical Specifications (Tech Specs), Operating License), mainly by the responsible engineer, a total of 40 hours will be assigned to the responsible engineer to perform this activity; 10 hours will be assigned to the resource engineer. The activity should be performed in a 2-week timeframe. Since changes to the SAR are required, and it is known that the change only involves updating a figure or drawing, a total of 5 hours will be assigned to the responsible engineer, with a duration of 1 week. There is no need to allocate hours to the resource engineer for this activity. The estimates for person-hours and activity duration are shown in Table 9.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
50.59/72.48 Review	40	10	2 week
SAR Update	5	0	1 week

Table 9. Estimate for 50.59/72.48 Review

4.2.15. Programs Impact Review

The review of engineering programs to incorporate any design change impact is included in the SDP Design Attribute Review (DAR). The DAR is a review performed during development of an Engineering Change to determine applicable or impacted engineering disciplines, engineering programs and stakeholders from other departments, areas or programs (SDPSC, 2017). For this case study, the first part of the DAR was performed in the scope definition when the engineering disciplines were identified. This section focuses on the second portion of the DAR, Engineering Topics/Programs.

A list of engineering topics and programs that could be impacted by a design change is shown in Attachment 10 of the SDP (SDPSC, 2017). Some of these include:

- Environmental Qualification (EQ),
- Fire Protection, Appendix R, and NFPA 0805 (i.e., National Fire Protection Association),
- FLEX (i.e., post-Fukushima strategies),
- License Renewal and Aging Management,
- Maintenance Rule, and
- MOVs (i.e., motor operated valves), AOVs (i.e., air operated valves), Relief Valves, and Check Valves.

Another list of engineering programs can also be found in INPO's document 15-003, "Conduct of Engineering Programs at Nuclear Power Stations." INPO's document includes a description of each program, what caused the program to be created, and the key aspects monitored under the program.

During the conceptual design phase, a preliminary review of programs should be performed. The process to conduct this review should be part of a plant-specific procedure. Usually, forms are provided and should be filled as part of the design change package. For this case study, a total of 30 hours will be allocated to this activity for the responsible engineer. The impacted programs should be identified by the end of the conceptual design phase. At least two weeks should be assigned as the duration time of this activity. Assistance from the resource engineer might be needed but are not being assumed in this case study. The estimates for person-hours and activity duration are shown in Table 10.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Programs Impact Review	30	0	2 weeks

Table 10. Estimate for Programs Impact Review

4.2.16. Design Reviews

This portion of the process involves two main activities: internal review of the conceptual design by each engineering discipline's SME and stakeholder review by plant personnel. Since the engineers working on this conceptual design are external to the plant, a design review should be performed by SME's from the same company or firm as the engineers. This review will ensure that the conceptual design is technically correct before presenting it to the customer. During other design phases, verification will be needed. The difference between review and verification is that a review can be performed by individuals that are familiar with the design while a verification is performed by individuals completely independent from the design. For this case study, 20 hours will be allocated to the mechanical review and 10 hours to the civil/structural review, with one-week duration. The estimates for person-hours and activity duration are shown in Table 11.

Activity	Person-Hour		Duration
	SME (mechanical)	SME (civil/structural)	
SME Internal Review	20	10	1 week

Table 11. Estimate for SME Internal Review

4.2.17. Estimates for Next Phases

By the end of the conceptual design phase the responsible and resource engineers should be familiar with the scope of the project and the impact the design change will have on plant documents and processes. Therefore, this is the best time to develop person-hour estimates for the technical portion of the remaining phases of the project. These estimates might also be required by the plant to approve the project to continue to the next stage. Given the scope presented for this case study, 20 hours could be assigned to the responsible engineer to develop the estimate. Ten total hours should also be allocated for the resource engineer to support the responsible engineer with one-week duration. The estimates for person-hours and activity duration are shown in Table 12.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Next Phase Estimate	20	10	1 week

Table 12. Estimate for Next Design Phase

4.2.18. Conceptual Impact Review Meeting

A conceptual design meeting should be held after the conceptual design package has been issued to the plant. The purpose of this meeting is to present the conceptual design to different plant departments, answer questions from stakeholders, and to obtain feedback on the design. In some plants, the conceptual design meeting is also a platform for plant management to decide if the design should continue to the next phases and to approve the budget to do so. Per the SDP, the design package should be submitted to stakeholders at least one week before the meeting. For estimations purposes, hours should be allocated for the engineers to develop a presentation for this meeting and to attend the meeting. Because of this, 15 hours will be allocated for the responsible engineer, and 5 hours will be allocated for the resource engineer's assistance. It is a good practice for all engineering disciplines involved with the design to be present at the meeting since technical questions may arise that cannot be answered by the responsible engineer alone. The estimates for person-hours and activity duration are shown in Table 13.

Activity	Person-Hour		Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	
Conceptual Design Meeting	15	5	1 week

Table 13. Estimate for Conceptual Design Meeting

4.2.19. Conceptual Design Estimate

The totals for the conceptual design estimates are shown in Table 14. As mentioned previously, these estimates are for the technical portion of the project and should be an input to the development of offer letters and project schedules, which are outside of the scope of engineering.

Activity	Person-Hour				Duration
	Responsible Engineer (mechanical)	Resource Engineer (civil/structural)	SME (mechanical)	SME (civil/structural)	
Define Project	20	5	0	0	1 week
Walkdowns	60	15	0	0	11 weeks
Design Inputs	90	30	0	0	11 weeks
New Drawings	40	20	0	0	2 weeks
Impacted Drawings	8	0	0	0	1 week
Drawing Peer Review	0	0	5	1	1 week
Calculations	80	0	0	0	2 weeks
Calculation Peer Review	0	0	40	0	1 week
Identification of Impacted Procedures	20	10	0	0	1 week
Design Basis Documents	20	10	0	0	1 week
Bill of Materials	20	20	0	0	8 weeks
50.59/72.48 Review	40	10	0	0	2 week
SAR Update	5	0	0	0	1 week
Programs Impact Review	30	0	0	0	2 weeks
SME Internal Review	0	0	20	10	1 week
Next Phase Estimate	20	10	0	0	1 week
Conceptual Design Meeting	15	5	0	0	1 week
TOTAL	468	135	65	11	= 679 hours

Table 14. Complete Estimate for Conceptual Design Phase

4.2.20. Conceptual Design Schedule

The activities and estimates presented in this section can be captured in a schedule as shown in Figure 21 and Figure 22. This schedule serves as an input to the project's overall schedule which should be created and maintained by the project manager. The estimate only addresses technical activities. Management or financial activities are not covered under this estimate. The description of activities and estimates provided in this section will be used to identify project risks and possible mitigation methods which are shown in the next section.

ID	ℹ	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names	Budget Hours
1	🧍	📌	Define Project	1 wk	Mon 1/1/18	Fri 1/5/18		Principal Engineer,Resource Engineer	25
2	🧍	📌	Walkdowns	11 wks	Mon 1/1/18	Fri 3/16/18		Principal Engineer,Resource Engineer	75
3	🧍	📌	Design Inputs	11 wks	Mon 1/1/18	Fri 3/16/18		Principal Engineer,Resource Engineer	120
4	🧍	📌	New Drawings	2 wks	Mon 1/8/18	Fri 1/19/18		Principal Engineer,Resource Engineer	60
5	🧍	📌	Impacted Drawings	1 wk	Mon 1/15/18	Fri 1/19/18		Principal Engineer	8
6		📌	Drawing Peer Review	1 wk	Mon 1/22/18	Fri 1/26/18	5	SME	6
7	🧍	📌	Calculations	2 wks	Mon 1/22/18	Fri 2/2/18		Principal Engineer,Resource	80
8		📌	Calculation Peer Review	1 wk	Mon 2/5/18	Fri 2/9/18	7	SME (x2)	40
9	🧍	📌	Identification of Impacted Procedures	1 wk	Mon 2/5/18	Fri 2/9/18		Principal Engineer,Resource Engineer	30
10	🧍	📌	Design Basis Documents	1 wk	Mon 2/12/18	Fri 2/16/18		Principal Engineer,Resource Engineer	30
11	🧍	📌	Bill of Materials	8 wks	Mon 1/22/18	Fri 3/16/18		Principal Engineer,Resource Engineer	40
12	🧍	📌	50.59/72.48 Review	2 wks	Mon 2/19/18	Fri 3/2/18		Principal Engineer,Resource Engineer	50
13	🧍	📌	SAR Update	1 wk	Mon 2/26/18	Fri 3/2/18		Principal Engineer	5
14	🧍	📌	Programs Impact Review	2 wks	Mon 3/5/18	Fri 3/16/18		Principal Engineer	30
15		📌	SME Internal Review	1 wk	Mon 3/19/18	Fri 3/23/18	1,3,4,5,7,9,1	SME	30
16		📌	Next Phase Estimate	1 wk	Mon 3/19/18	Fri 3/23/18		Principal Engineer,Resource Engineer	30
17		📌	Conceptual Design Meeting	1 wk	Mon 3/26/18	Fri 3/30/18		Principal Engineer,Resource Engineer	25

Figure 21. Conceptual Design Schedule – Task, Duration, Resources, and Budget Hours (Microsoft Project)

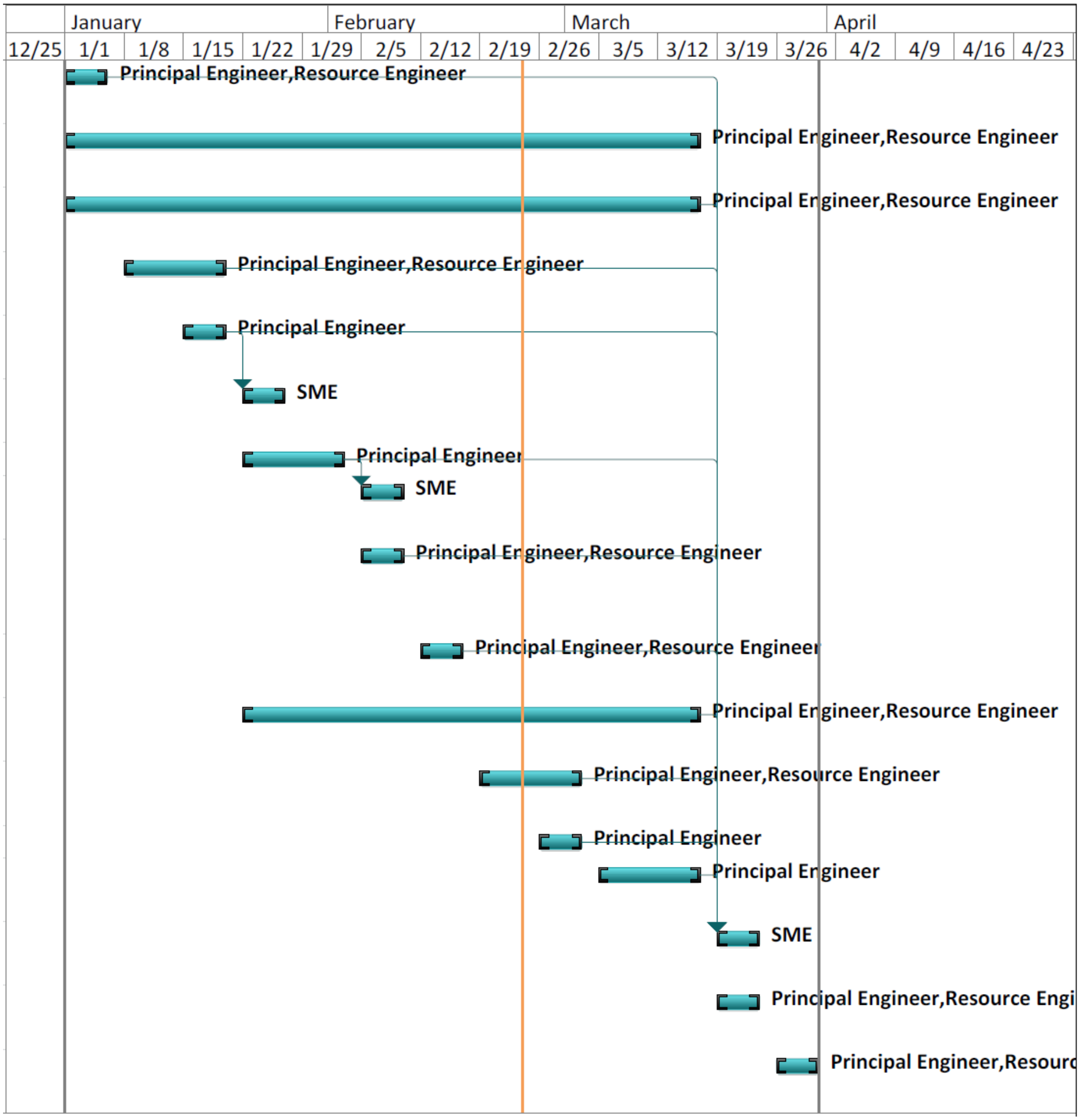

Figure 22. Conceptual Design Schedule – Timeline (Microsoft Project)

4.3. Part III: Risks

Risk, by definition, is the product of the likelihood and consequence associated with an adverse outcome (INPO, 2015). Project risks can often be identified, and mitigation strategies can be put in place to avoid delays in schedule and increases in cost. There are various tools used in the industry to identify risks. Some of the most common tools are Preliminary Hazard Analysis (PHA), Hazard and Operability Analysis (HAZOP), Job Safety Analysis (JSA), Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Cause and Consequences Analysis (CCA), among others. These tools' purpose is to identify failure modes, or risks, and to find ways to mitigate their effects.

This case study applies the Failure Mode and Effects Analysis (FMEA) tool to identify risks that can arise during the development of the conceptual design discussed in Section 4.2. An FMEA is an engineering analysis done by a cross-functional team of subject matter experts that thoroughly analyzes product designs or manufacturing processes, early in the product development process (Carlson, 2014). Each of the activities included in the conceptual design estimate and schedule from Section 4.2 is evaluated to identify potential failure modes, determine potential effects of failure, assign severity rating, identify potential causes of failure, assign occurrence rating, identify design controls to prevent and detect the failure, and assign detection rating. A risk priority number (RPN) is then calculated for each activity. The RPN is a numerical ranking of the risk of each potential failure mode/cause, made up of the arithmetic product of the three elements: severity of the effect, the likelihood of occurrence of the cause, and the likelihood of detection of the cause (Carlson, 2014). The RPN number is then used to create graphical representations of potential failure modes for each activity. The purpose of these graphs is to draw attention to the most significant failure modes within each activity. Recommendations on how to mitigate the risks are also provided.

In his 2014 paper, Carlson provides generic FMEA worksheets, severity scales, likelihood scales, and occurrence scales. Adapted versions of these are used in this case study. Instead of evaluating effects such as safety and regulatory requirements, the severity scale used for this case study assesses the impact on rework and safety or operability issues. The scale is ranked from “No Effect” to “Safety or Operability Issue” and is based on the effects the failure would have on the person-hour effort, schedule, deliverables, outage, and even plant shutdown. The likelihood of failure (i.e., occurrence) scale based on the experience the responsible and resource engineers have with nuclear power and the engineering design process and how that experience can help reduce the likelihood of the activity failures to occur, instead of identifying incidents per item. The occurrence scale is ranked from “Very Low” to “Very High” likelihood of failure. Instead of focusing on stages of detection, the detection scale is also based on engineers’ experience to detect issues. The scale is ranked from “Almost Certain” to “Absolute Uncertainty” of detecting issues before reaching the customer. The controls element of the FMEA is replaced by human performance (HU) tools that can be applied to prevent or detect the failure mode. These tools can be found in INPO’s report number 05-002 (INPO, 2007), “Human Performance Tools for Engineers and Other Knowledge Workers.”

The use of the FMEA tool to manage project risks relates to INPO’s Principles for Excellence in Integrated Risk Management as follows:

- Principle #1 – Corporate and nuclear leaders foster a culture that promotes risk awareness and effective risk management (INPO, 2015). Leaders can foster a culture of risk awareness by encouraging the use of risk assessment tools such as FMEA.

- Principle #2 – Individuals take responsibility for identifying and managing the risk inherent in their activities and demonstrate a personal commitment to nuclear safety (INPO, 2015). This principle is fulfilled by identifying potential failure modes for activities performed throughout the project's life.
- Principle #3 – High standards of risk recognition, management, and mitigation are embedded in corporate and station policies, programs and processes (INPO, 2015). The identification of potential effects of failure, potential causes of failure, and current design controls to prevent and detect failure describes the core of this principle.
- Principle #4 – A consequence-biased approach is applied to risk determination, and decision-making reflects an intolerance for unacceptable end states (INPO, 2015). The calculation of the RPN can help individuals distinguish acceptable from unacceptable risks.
- Principle #5 – Risk is eliminated or minimized through pre-emptive actions based on a well-defined understanding of event significance and consequence. Residual risk is mitigated to acceptable levels using compensatory measures (INPO, 2015). The development of FMEA recommended actions and RPN describe this principle.
- Principle #6 – Leaders and individuals communicate risk effectively among the nuclear division, corporate executives and other key stakeholders, including the board of directors (INPO, 2015). After an FMEA is performed for a project, the

results of such analysis should be communicated to team members to create an awareness of potential risks and to provide possible mitigation techniques.

- Principle #7 – Periodic effectiveness reviews are performed to promote continuous learning and to improve risk management across the organization (INPO, 2015). These are translated into the various reviews performed throughout the project and stem from peer reviews of individual deliverables to the internal review of the design package.

The accurate application of these principles to the development of a project could guarantee excellence, thus contributing to the Delivering the Nuclear Promise initiative within the nuclear industry.

4.3.1. FMEA Severity Scale

The severity scale used for this case study is based on the amount of effort that the activity's failure mode could potentially add to the project. The scale is divided into three main categories: "Safety or Operability Issue," "Rework," and "No Effect." The "No Effect," lowest ranking category, is based on the failure not affecting project schedule or deliverables. "Safety or Operability Issue," the highest category, is based on the activity failure' potential to introduce a new safety hazard at the plant or to create an operability issue which could lead to a plant shutdown. The "Rework" category is divided into eight (8) different ranks. These differentiate the effort, in time, needed to recuperate from the error and the effect it will have on the project schedule, deliverables, installation, and outage schedule. The generated severity scale is shown in Table 15.

Category	Criteria	Rank
Safety or Operability Issue	Creates a new safety hazard or plant operability issue (i.e., leading to plant shutdown)	10
Rework	Significate effort; could impact implementation and/or outage schedule	9
	More than 1 month effort; may have some impact on implementation and/or outage schedule	8
	More than 1 month effort; has some impact on schedule and may impact deliverables	7
	More than 2 week effort but less than 1 month; has some impact on schedule and may impact deliverables	6
	More than 1 week effort but less than 2 weeks; has some impact on schedule but not on deliverables	5
	More than 1 day effort but less than 1 week; has some impact on schedule but not on deliverables	4
	More than 1 hour effort but less than 1 day; has no impact on schedule nor deliverables	3
	Less than 1 hour effort; has no impact on schedule nor deliverables	2
No Effect	None	1

Table 15. FMEA Severity Scale

4.3.2. FMEA Likelihood of Failure Scale

The likelihood of failure scale used for this case study is based on the experience the responsible and resource engineers have with nuclear power and the engineering design process and how that experience can help reduce the likelihood of the activity failures to occur. The scale is divided into five (5) categories ranging from “Very Low” likelihood of failure to “Very High” likelihood of failure. The “Very Low” likelihood of failure corresponds to engineers having 10 or more years of experience within the nuclear power industry and having extensive experience with engineering modification projects. The “Very High” likelihood of failure corresponds to engineers having less than one year of experience within the nuclear power industry and engineering modification projects. Ranks were assigned to each category and range from 1 (“Very Low”) to 5 (“Very High”). The categories in between are focused on experience and capability of the resource engineers. The likelihood of failure scale is shown in Table 16.

Likelihood of Failure	Criteria	Rank
Very High	Responsible and resource engineers are new (i.e., 1 year or less) within the nuclear power industry and to engineering modification projects.	5
High	Responsible and/or resource engineers are experienced (i.e., 10 or more years) within the nuclear power industry, but have no experience engineering modification projects.	4
Moderate	Responsible and resource engineers are somewhat experienced (i.e., five to ten years) within the nuclear power industry with at least half of their experience focused in engineering modification projects.	3
Low	Responsible and resource engineers are experienced (i.e., 10 or more years) within the nuclear power industry with at least half of their experience focused in engineering modification projects.	2
Very Low	Responsible and resource engineers are experienced (i.e., 10 or more years) within the nuclear power industry and have extensive experience with engineering modification projects.	1

Table 16. FMEA Likelihood of Failure Scale

4.3.3. FMEA Opportunity for Detection Scale

Similar to the likelihood of failure scale, the opportunity for detection scale used for this case study is based on the experience the responsible and resource engineers have with nuclear power and the engineering design process. The scale focuses on how the engineers' expertise can help in the detection of failures within the activities before the failures reach or affect the customer. The scale is divided into seven (7) categories ranging from "Almost Certain" likelihood of failure to "Absolute Uncertainty" when it comes to opportunities for detecting failures. Ranks were assigned to each category and range from 1 ("Almost Certain" – failure is likely to be detected) to 7 ("Absolute Uncertainty" – failure cannot be detected). The categories in between are focused on experience and capability of the resource engineers, similar to the likelihood scale. The generated opportunity for detection scale is shown in Table 17.

Opportunity for Detection (before reaching customer)	Criteria	Rank
Absolute Uncertainty	No controls are in place to detect failure. Failure cannot be detected.	7
Very Low	Responsible and resource engineers are new (i.e., 1 year or less) within the nuclear power industry and to engineering modification projects.	6
Low	Responsible and/or resource engineers are experienced (i.e., 10 or more years) within the nuclear power industry, but have no experience engineering modification projects.	5
Medium	Responsible and resource engineers are somewhat experienced (i.e., five to ten years) within the nuclear power industry with at least half of their experience focused in engineering modification projects.	4
High	Responsible and resource engineers are experienced (i.e., 10 or more years) within the nuclear power industry with at least half of their experience focused in engineering modification projects.	3
Very High	Responsible and resource engineers are experienced (i.e., 10 or more years) within the nuclear power industry and have extensive experience with engineering modification projects.	2
Almost Certain	Controls are in place to detect failure.	1

Table 17. FMEA Opportunity for Detection Scale

4.3.4. Resources

The resources for this case study, as described in Section 4.2, are the principal engineer, resource engineer and subject matter experts (SMEs). For this FMEA the following experience will be taken into consideration when evaluating the activities:

- Principal engineer – A Mechanical engineer with more than ten (10) years in the nuclear industry and approximately six (6) years of engineering design experience.
- Resource engineer – Civil/structural engineer with more than twelve (12) years of experience in the nuclear industry and approximately four years of engineering design experience.
- SME – The SMEs are mechanical and civil/structural engineers with more than 15 years of experience in the nuclear industry and with more than ten (10) years of engineering design experience.

These descriptions will be applied when evaluating the likelihood of failure and opportunity for detection for each activity. Most of the activities evaluated next are performed by the responsible engineer or by resource engineers. These engineers are experienced (i.e., 10 or more years) within the nuclear power industry with at least half of their experience focused on engineering modification projects. Therefore, an occurrence rating of 2 and detection rating of 3 is assigned to each of these activities.

4.3.5. FMEA for Define Project

The definition of the project could be the most important activity in the development of a design. This activity defines the entire project. Two failure modes were identified for this activity. These are:

- FM.1.1 – Project not correctly defined
- FM.1.2 – Not all pertinent information received from the customer

Table 18 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. As shown in the table, the identified failure modes can cause significant issues with schedule and deliverables. Changes in scope, especially late during the design, could lead to delays in implementation or even on outage schedule. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ranking numbers are shown in Table 19 and Figure 23. The FMEA table shows FM.1.2, not all pertinent information received from the customer, as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Define Project	FM.1.1	Changes in the project scope will occur which can impact cost and schedule	Information missed during customer meetings	Technical Task Prejob Briefing Self-Checking Questioning Attitude Validate Assumptions	Maintain constant communication with the customer, specifically with customer SMEs.
		Customer dissatisfaction	Walkdowns not performed		
	FM.1.2	Changes in the project scope will occur which can impact cost and schedule	Customer did not have a clear requirement when the project was assigned	Technical Task Prejob Briefing Questioning Attitude Validate Assumptions	Maintain constant communication with the customer, specifically with customer SMEs. Research of OE can help the customer identify issues that were not considered.
			New requirements were created during the development of the design		

Table 18. Failure Modes, Effects, Causes, and Recommendations – Define Project

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Define Project	FM.1.1	7	2	3	42
	FM.1.2	9	2	3	54

Table 19. Failure Mode Ranking Numbers – Define Project

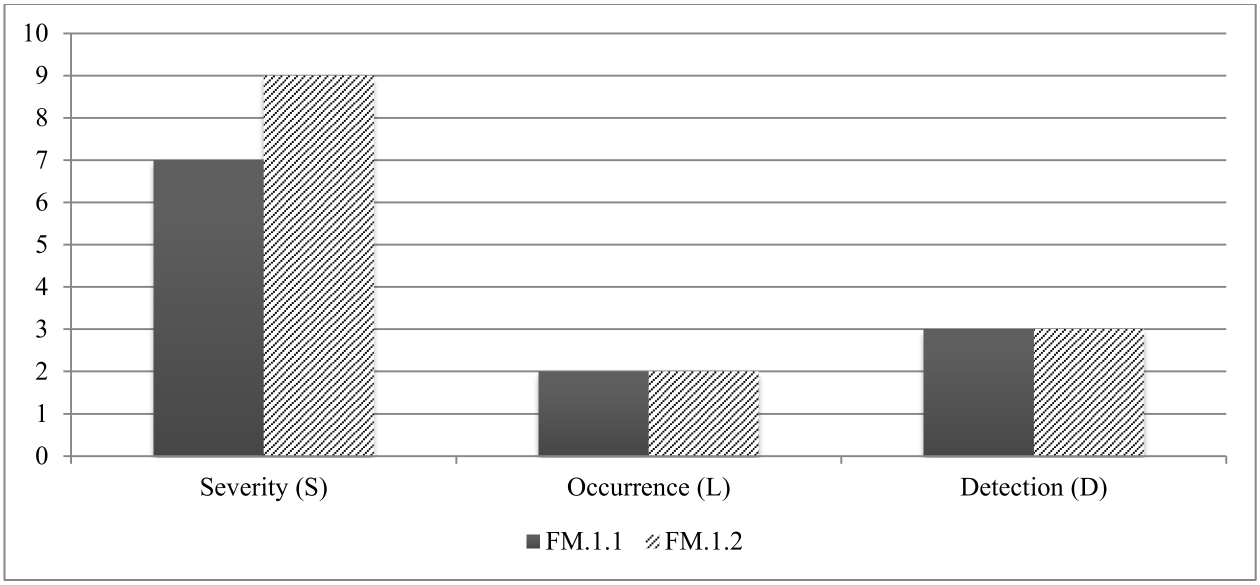

Figure 23. Failure Mode Ranking Numbers – Define Project

4.3.6. FMEA for Walkdowns

As described in Section 4.2.3, walkdowns should be performed pre-design and during the development of the design. Three failure modes were identified for this activity. These are:

- FM.2.1 – Wrong system/component was observed;
- FM.2.2 – Area cannot be accessed;
- FM.2.3 – Correct tools (i.e., camera, tape measurer, etc.) are not available.

Table 20 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions.

The most severe of the failure modes is FM.2.1. If the wrong system or component is observed during a walkdown, this could lead to future changes in design that were not accounted for, which could at the same time impact schedule and deliverables. The responsible and resource engineers perform walkdowns. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 21 and Figure 24. The FMEA table shows FM.2.1, wrong system/component, was observed as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Walkdowns	FM.2.1	Changes in design could occur which could also impact cost and schedule	Incorrect interpretation of drawings Information obtained from sources not familiar with the system/ component	Technical Task Prejob Briefing Self-Checking Questioning Attitude	Include customer SMEs to walkdown plans.
	FM.2.2	Assumptions would be put in place that would need validation in the future	Work planned by others Walkdown scheduled without consulting correct stakeholders	Self-Checking Validate Assumptions Project Planning	Coordinate walkdowns with the customer. Involvement of customer SMEs could help engineers identify any issues with accessing areas of the plant.
	FM.2.3	More walkdowns may be required	Engineers are not prepared to perform the walldown	Technical Task Prejob Briefing	Engineers should ensure that tools are available for walkdowns. Pre-job briefs can help identify any issues with obtaining the necessary tools.

Table 20. Failure Modes, Effects, Causes, and Recommendations – Walkdowns

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Walkdowns	FM.2.1	7	2	3	42
	FM.2.2	5	2	3	30
	FM.2.3	4	2	3	24

Table 21. Failure Mode Ranking Numbers – Walkdowns

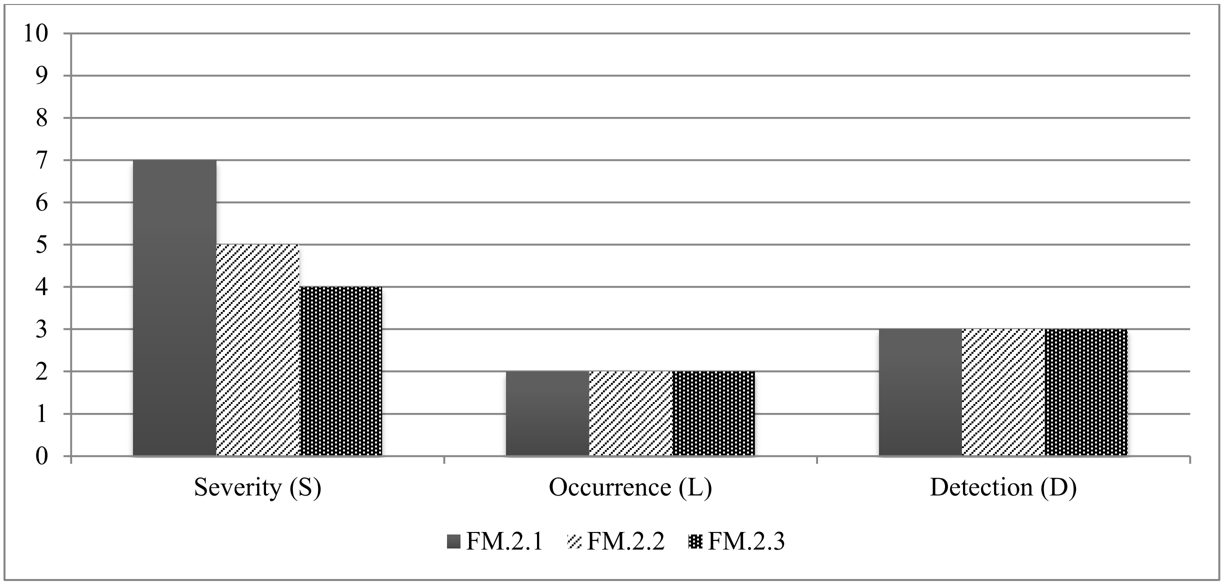

Figure 24. Failure Mode Ranking Numbers – Walkdowns

4.3.7. FMEA for Design Inputs

During the conceptual design phase, the identification of design inputs is an essential task since it will determine how the design will progress. If some design inputs are not considered during this phase or are incorrectly identified, this could lead to severe effects. One failure mode was identified for this activity. This is:

- FM.3.1 – Design inputs not considered or incorrectly identified

Table 22 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. This failure mode could cause significant rework that could lead to changes in schedule and deliverables, especially since there is a potential for some of the work for future phases not to have been estimated. The responsible and resource engineers perform this activity. The severity, occurrence, and detection rankings for the failure modes identified are shown in Table 23 and Figure 25.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Design Inputs	FM.3.1	Design parameters are not incorporated into design (e.g., dimensions)	Improper review of existing documents related to the system or component	Self-Checking Questioning Attitude Validate Assumptions Peer Review	Ensure the proper reviews are being performed by knowledgeable SMEs. Consultation with customer SMEs may also be beneficial.
		Incorrect materials specified			
		Impacted documents not identified			
		Incorrect estimation of effort for future phases			

Table 22. Failure Modes, Effects, and Causes, and Recommendations – Design Inputs

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Design Inputs	FM.3.1	7	2	3	42

Table 23. Failure Mode Ranking Numbers – Design Inputs

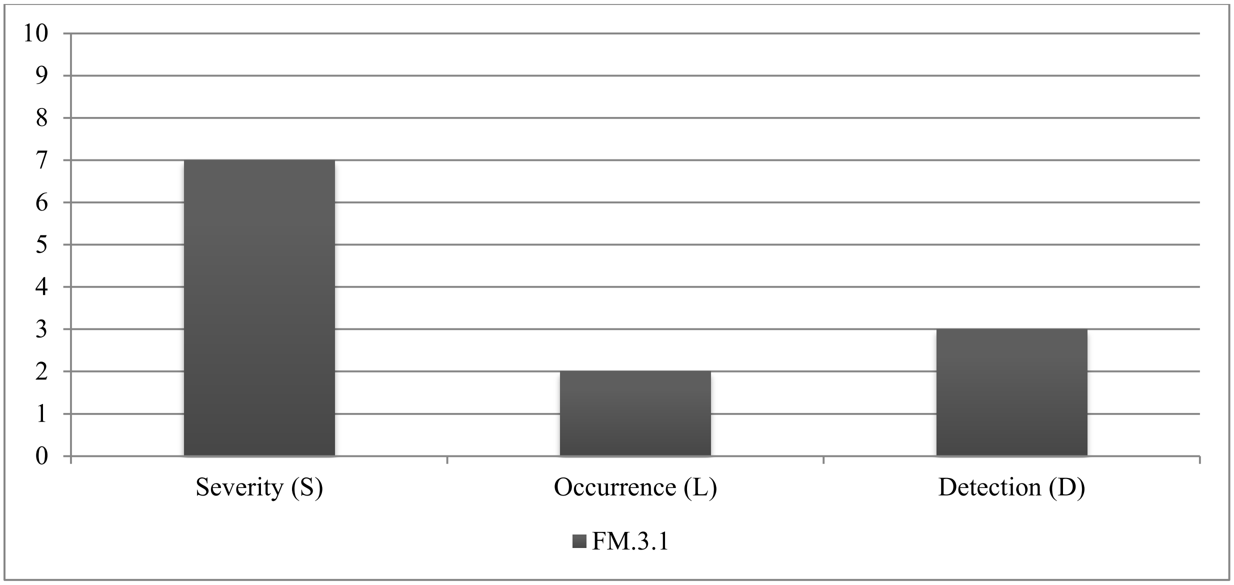

Figure 25. Failure Mode Ranking Numbers – Design Inputs

4.3.8. FMEA for New Drawings

Two failure modes were identified for the identification and creation of new drawings activity. These are:

- FM.4.1 – Not all new drawings are identified;
- FM.4.2 – Drawing does not capture the scope.

Table 24 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. Recognizing the need to create new drawings during the conceptual design phase is essential since it will determine the amount of effort for the next design phases. Even though it best to identify these drawings early in the design, it is not imperative to initiate all drawings during the conceptual design phase. The effort to recuperate from an error like this could be as easy as listing the drawing within the package. This effort can be minimal as long as it is caught during the conceptual design. If drawings do not capture the scope correctly, even though it is significant, the effort to correct this failure can be easily detected by knowledgeable reviewers. These drawings should be updated as soon as possible and before they are presented to the customer.

All of the identified failure effects could cause rework that could lead to changes in schedule and deliverables, especially since there is a potential for some of the work for future phases not to have been estimated. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 25 and Figure 26. The FMEA table shows FM.4.1, though not all new drawings are identified, as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
New Drawings	FM.4.1	New drawings will need to be developed during future design phases Effort to develop new drawings may not be accounted for during estimation	Engineers are not familiar with the plant's drawings system	Self-Checking Questioning Attitude Validate Assumptions Peer Review	Ensure engineers and SME reviewers are familiar with the scope of the project and the specific plant processes for drawings.
	FM.4.2	Rework to update drawings during future phases	Engineers are not familiar with the scope	Questioning Attitude Validate Assumptions	Ensure engineers have a thorough understanding of the project's scope and how it should be captured in drawings, specifically following plant requirements.

Table 24. Failure Modes, Effects, Causes, and Recommendations – New Drawings

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
New Drawings	FM.4.1	3	2	3	18
	FM.4.2	6	2	3	36

Table 25. Failure Mode Ranking Numbers – Design Inputs

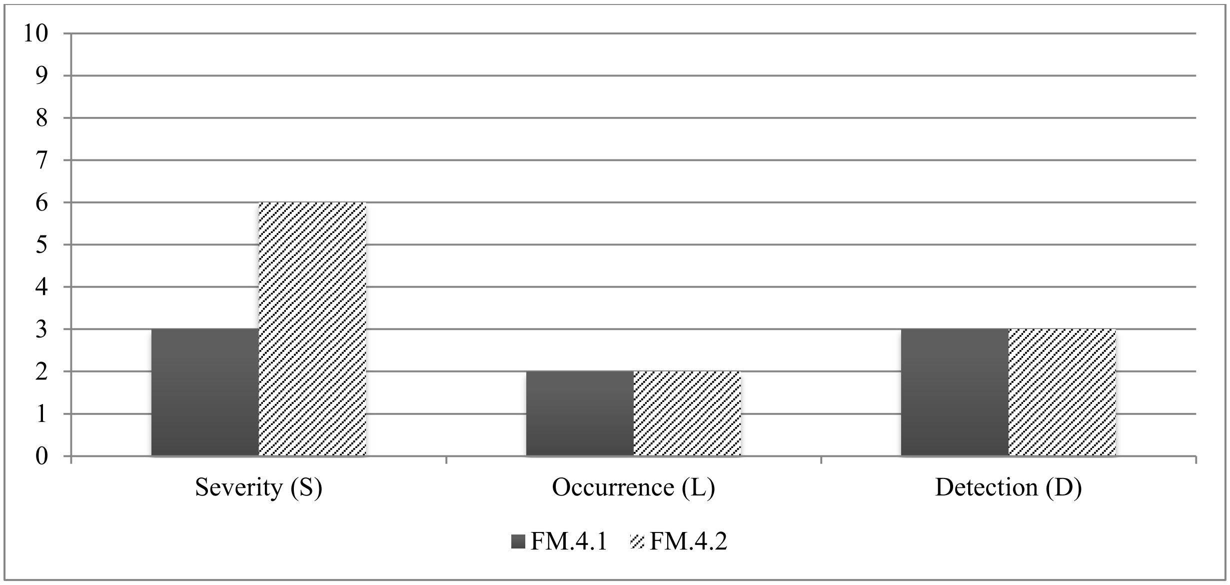

Figure 26. Failure Mode Ranking Numbers – New Drawings

4.3.9. FMEA for Impacted Drawings

Similar to the development of new drawings, two failure modes were identified for this activity. These are:

- FM.5.1 – Not all impacted drawings are identified;
- FM.5.2 – Drawing does not capture the scope.

Table 26 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The severity of the failure modes identified for this activity is lower than the creation of new drawings since it is not vital to identify all impacted drawings during the conceptual design phase, which can be a preliminary design. The effort to recuperate from an error like this could be as easy as listing the drawing within the package. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 26 and Figure 27. The FMEA table shows FM.5.2 as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Impacted Drawings	FM.5.1	Impacted drawings will need to be identified during future design phases	Engineers are not familiar with plant's drawings system	Self-Checking Questioning Attitude Validate Assumptions Peer Review	Ensure engineers and SME reviewers are familiar with the scope of the project and the specific plant processes for drawings.
	FM.5.2	Rework to update drawings during future phases	Engineers are not familiar with plant's drawings system	Questioning Attitude Validate Assumptions	Ensure the effort is accounted for in estimates to identify impacted drawings in future design phases.

Table 26. Failure Modes, Effects, Causes, and Recommendations – Impacted Drawings

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Impacted Drawings	FM.5.1	2	2	3	12
	FM.5.2	2	2	3	30

Table 27. Failure Mode Ranking Numbers – Impacted Drawings

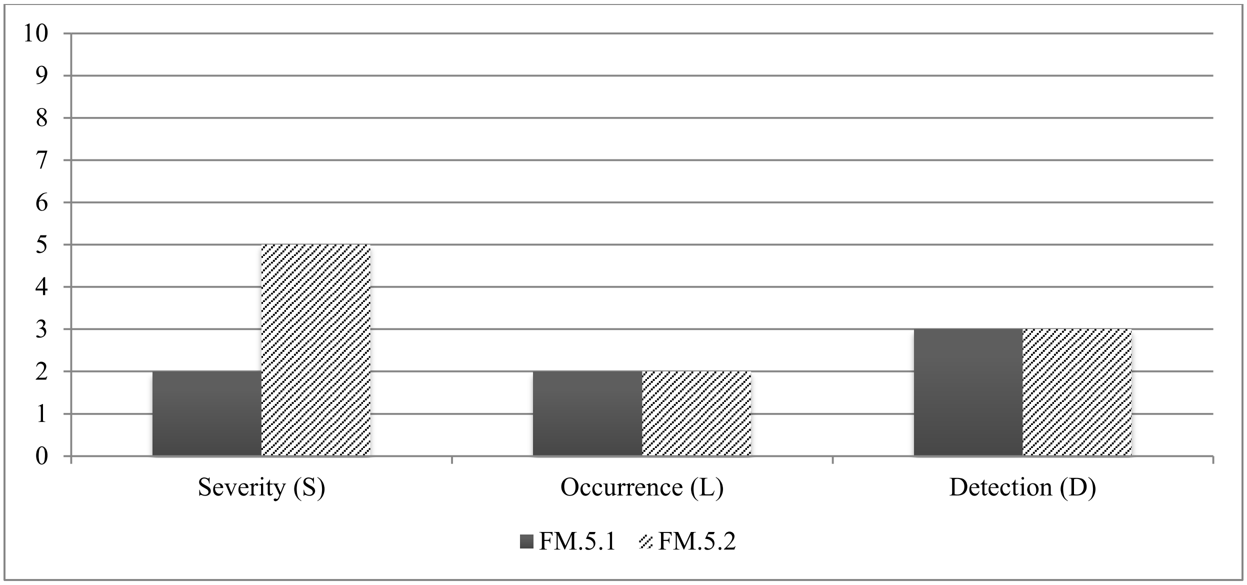

Figure 27. Failure Mode Ranking Numbers – Impacted Drawings

4.3.10. FMEA for Drawing Peer Review

This activity involves the peer review of new and impacted drawings and is performed by knowledgeable SMEs. More than one SME might be required depending on the discipline of each drawing. Three failure modes were identified for this activity. These are:

- FM.6.1 – Review did not catch evident errors;
- FM.6.2 – Reviewer is not the proper SME;
- FM.6.3 – Reviewer is not qualified to review drawings.

Table 28 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. As stated in Section 4.2, this activity is performed by the knowledgeable SMEs. The SMEs in this case study are experienced (i.e., 10 or more years) within the nuclear power industry with extensive experience focused on engineering modification projects. Therefore, an occurrence rating of 1 and detection rating of 2 is assigned. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 29 and Figure 28. The FMEA table shows FM.6.1 as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Drawing Peer Review	FM.6.1	Drawing is issued to the customer with errors	Reviewer was not familiar with the scope of the project	Questioning Attitude Validate Assumptions Peer Review	Ensure reviewers are assigned early in the process to ensure they are available when needed and that proper time is allotted for their review.
			Reviewer did not take the time to perform a thorough review		
	FM.6.2	Errors in drawing can be missed	Qualified resources may not have been available to perform the review	Questioning Attitude Project Planning	Individuals should ensure they are knowledgeable on a topic before accepting to perform work.
	FM.6.3	Drawing review might not fulfil customer's requirements	Qualified resources may not have been available to perform the review	Questioning Attitude Validate Assumptions Peer Review	Always ensure assigned reviewers are qualified to the process they are reviewing under.

Table 28. Failure Modes, Effects, Causes, and Recommendations –Drawings Peer Review

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Drawing Peer Review	FM.6.1	6	1	2	12
	FM.6.2	5	1	2	10
	FM.6.3	4	1	2	8

Table 29. Failure Mode Ranking Numbers – Drawings Peer Review

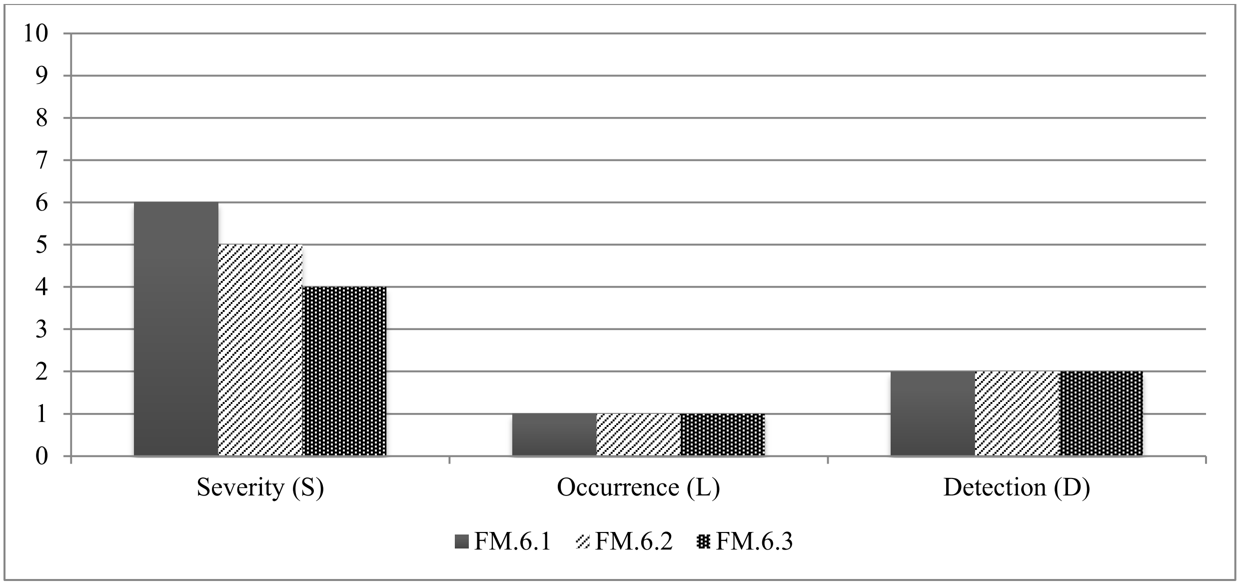

Figure 28. Failure Mode Ranking Numbers – Drawings Peer Review

4.3.11. FMEA for Calculations

Calculations are a vital part of any design. They typically justify a design using mathematical evaluations. Calculations can be as simple as calculating the flow through a short piece of pipe or as complicated as generating a pipe stress analysis of an entire piping arrangement. Due to the amount of effort it takes to complete a calculation (i.e., develop technical content, reviews, verifications, etc.) errors such as not identifying impacted calculations or not using correct methods can result in adverse effects for a project. Four failure modes were identified for this activity. These are:

- FM.7.1 – Wrong design inputs were considered;
- FM.7.2 – Impacted calculations were not identified;
- FM.7.3 – Calculation method is not appropriate;
- FM.7.4 – Originator is not qualified to perform the calculation.

Table 30 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 31 and Figure 29. The FMEA table shows FM.7.2 as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Calculations	FM.7.1	Calculation results may not be accurate	Improper review of existing documents related to the system or component	Questioning Attitude Validate Assumptions Problem-Solving	Communication with customer's SME could help identify design inputs.
	FM.7.2	Effort to develop calculations during next design phases may not have been estimated.	Engineers are not familiar with the plant's calculation system	Questioning Attitude Validate Assumptions Problem-Solving	Communication with customer's SME could help identify other potential impacted calculations.
	FM.7.3	Calculation may not be accepted by the customer	Engineers are not familiar with the plant's calculation process or with the topic	Questioning Attitude Validate Assumptions Problem-Solving	Discussions with SME's and review of OE can help identify appropriate methods.
	FM.7.4	Calculation might not fulfil customer's requirements	Qualified resources may not have been available to perform the calculation	Questioning Attitude Validate Assumptions Problem-Solving	Always ensure the assigned originators are qualified to the plant's calculation process.

Table 30. Failure Modes, Effects, Causes, and Recommendations – Calculations

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Calculations	FM.7.1	6	2	3	36
	FM.7.2	9	2	3	54
	FM.7.3	8	2	3	48
	FM.7.4	6	2	3	36

Table 31. Failure Mode Ranking Numbers – Calculations

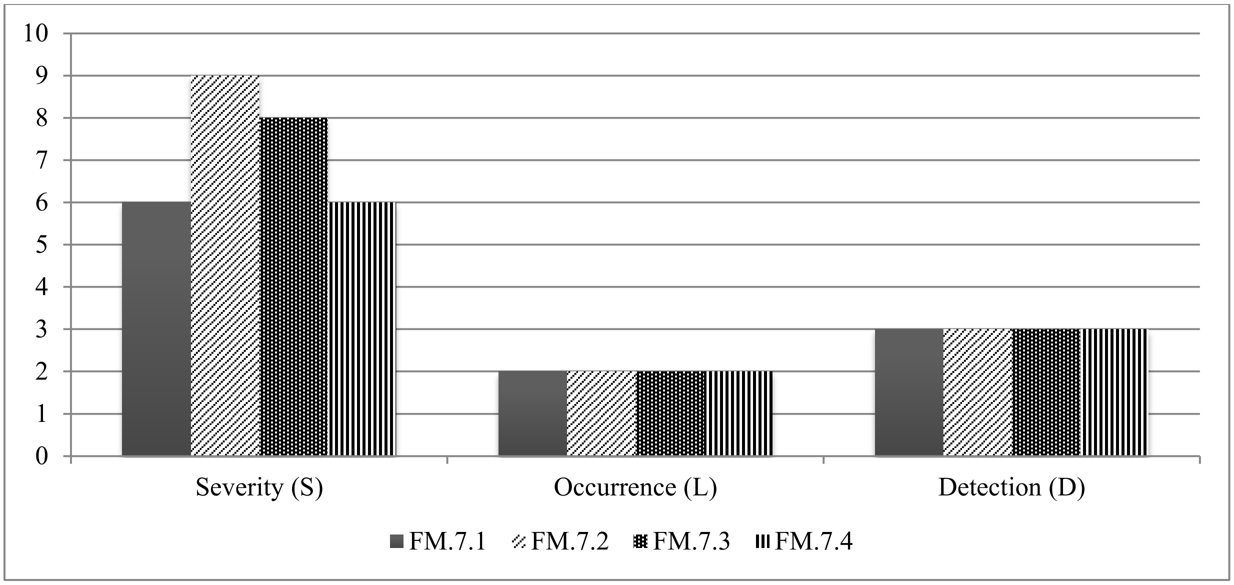

Figure 29. Failure Mode Ranking Numbers – Calculations

4.3.12. FMEA for Calculation Peer Review

At the conceptual design phase not correctly reviewing or verifying a calculation could impact future design phases. At this stage, the impact is not as severe as the creation of new calculations since the review/verification is not final. Final reviews and/or verifications are performed after the final design is complete. Three failure modes were identified for this activity. These are:

- FM.8.1 – Verification did not catch evident errors;
- FM.8.2 – Verifier is not the proper SME;
- FM.8.3 – Verifier is not qualified to review calculations.

Table 32 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. SMEs perform this activity. The SMEs in this case study are experienced (i.e., 10 or more years) within the nuclear power industry with extensive experience focused on engineering modification projects. Therefore, an occurrence rating of 1 and detection rating of 3 is assigned. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 33 and Figure 30. The FMEA table shows FM.8.1 as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Calculation Peer Review	FM.8.1	Calculation is issued to the customer with errors	Verifier was not familiar with the scope of the project Verifier did not take the time to perform a thorough verification	Peer Review Questioning Attitude Technical Task Prejob Briefing	A peer review performed by another resource may be beneficial in identifying errors.
	FM.8.2	Errors in the calculation can be missed	Qualified resources may have not been available to perform the verification	Project Planning Questioning Attitude	Individuals should ensure they are knowledgeable on a topic before accepting to perform work.
	FM.8.3	Calculation review might not fulfil customer's requirements	Qualified resources may have not been available to perform the verification	Project Planning Questioning Attitude	Always ensure assigned verifiers are qualified to the process they are verifying under.

Table 32. Failure Modes, Effects, Causes, and Recommendations – Calculation Peer Review

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Calculation Peer Review	FM.8.1	7	1	3	21
	FM.8.2	6	1	3	18
	FM.8.3	5	1	3	15

Table 33. Failure Mode Ranking Numbers – Calculation Peer Review

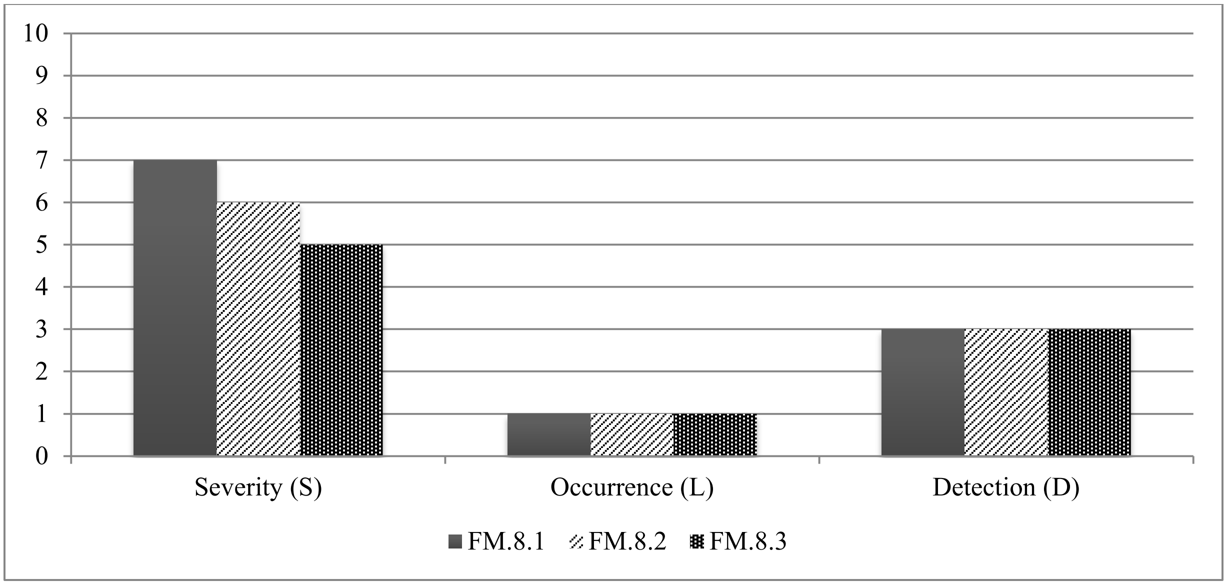

Figure 30. Failure Mode Ranking Numbers – Calculation Peer Review

4.3.13. FMEA for Identification of Impacted Procedures

Plant operating procedures impacted by a design change can be identified during different phases of a project, especially during plant stakeholder reviews. These procedures are updated after, or right before, a new design is implemented. Non-engineers typically perform the update or creation of procedures. Only one failure mode was identified for this activity:

- FM.9.1 – Not all impacted procedures are identified.

Table 34 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 35 and Figure 31.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Identification of Impacted Procedures	FM.9.1	Not all procedures are updated with current plant design.	A comprehensive review of potentially impacted procedures was not performed by the engineers.	Questioning Attitude Self-Checking	Always ensure that the resource engineers provide support in identifying affected documents.

Table 34. Failure Modes, Effects, Causes, and Recommendations – Identification of Impacted Procedures

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Identification of Impacted Procedures	FM.9.1	4	2	3	24

Table 35. Failure Mode Ranking Numbers – Identification of Impacted Procedures

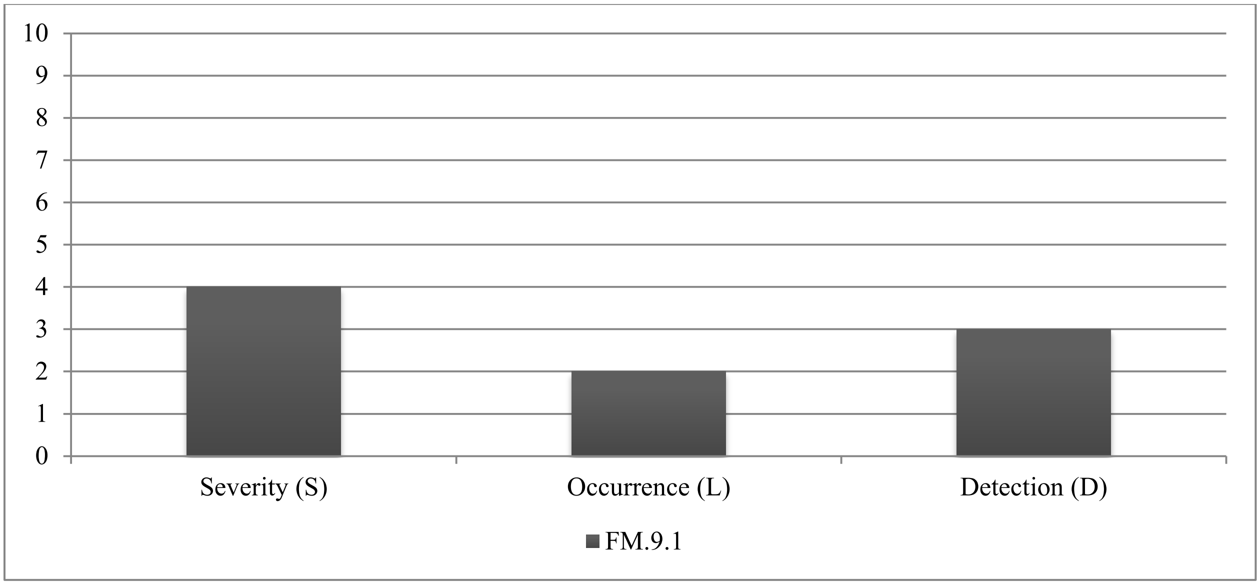

Figure 31. Failure Mode Ranking Numbers – Identification of Impacted Procedures

4.3.14. FMEA for Design Basis Documents

Similar to the identification of impacted procedures, the identification of design basis documents can be identified during different phases of a project. These documents are updated outside of the design process. Markups are typically included in design packages for information only. Only one failure mode was identified for this activity:

- FM.10.1 – Not all impacted DBDs are identified.

Table 36 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 37 and Figure 32.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Design Basis Documents	FM.10.1	DBDs are not updated with current plant design.	A comprehensive review of existing DBDs was not performed by the engineers.	Questioning Attitude Self-Checking	Always ensure that the resource engineers provide support in identifying affected documents.

Table 36. Failure Modes, Effects, Causes, and Recommendations – Design Basis Documents

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Design Basis Documents	FM.10.1	4	2	3	24

Table 37. Failure Mode Ranking Numbers – Design Basis Documents

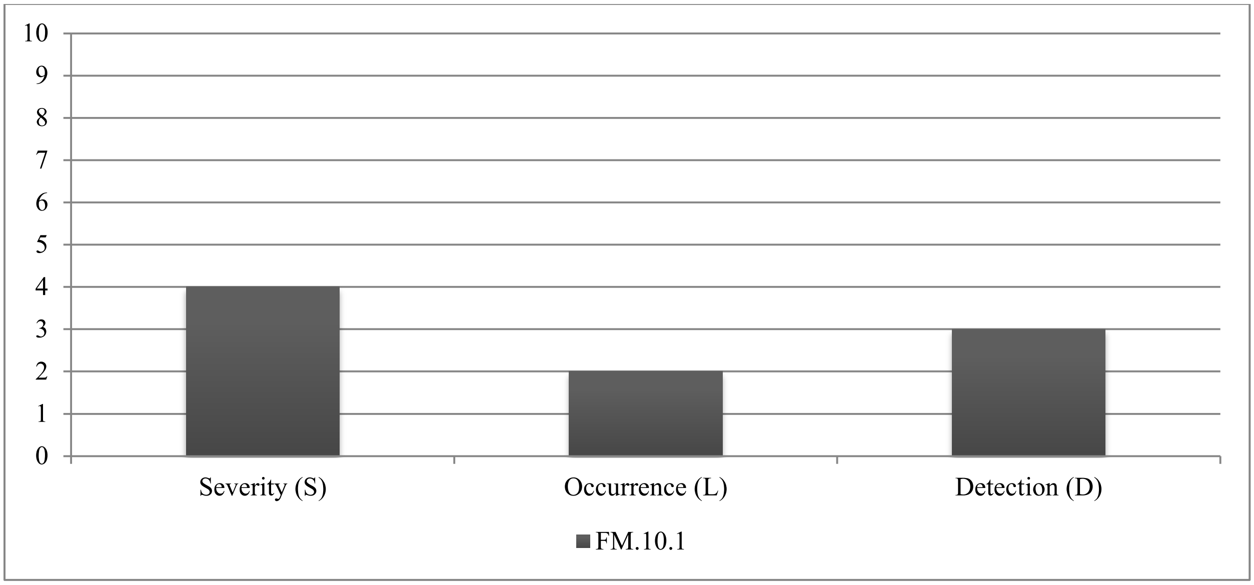

Figure 32. Failure Mode Ranking Numbers – Design Basis Documents

4.3.15. FMEA for Bill of Materials

During the conceptual design phase, a preliminary bill of materials (BOM) is developed based on the initial design. This list gets refined as the design progresses. A final or complete BOM is generated after the final design is complete. Because of this, not identifying all items in a BOM, or having errors, will more than likely not have a significant effect on a project. Three failure modes were identified for this activity. These are:

- FM.11.1 – Not all materials were added to the BOM;
- FM.11.2 – Items identified cannot be purchased or do not exist;
- FM.11.3 – Customer does not agree on materials chosen.

Table 38 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 39 and Figure 33. The FMEA table shows FM.11.3 as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Bill of Materials	FM.11.1	None. The design is conceptual. The list will be refined in the next design phase.	Design is preliminary	Questioning Attitude Validate Assumptions Self-Checking Peer Review Decision-Making	Include as many materials as possible in a BOM to represent the conceptual design.
	FM.11.2	Alternate items should be specified in the next design phase	Engineer did not perform sufficient research on items available in the market	Questioning Attitude Validate Assumptions Self-Checking Decision-Making	Always research possible vendors when choosing items to ensure the part or material is available in the market.
	FM.11.3	Changes in design during future phases	Customer and engineer have different views and/or opinions on the design	Questioning Attitude Validate Assumptions	Discussions with customer SMEs throughout the development of the design could help with the selection of materials.

Table 38. Failure Modes, Effects, Causes, and Recommendations – Bill of Materials

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Bill of Materials	FM.11.1	1	2	3	6
	FM.11.2	2	2	3	12
	FM.11.3	4	2	3	24

Table 39. Failure Mode Ranking Numbers – Bill of Materials

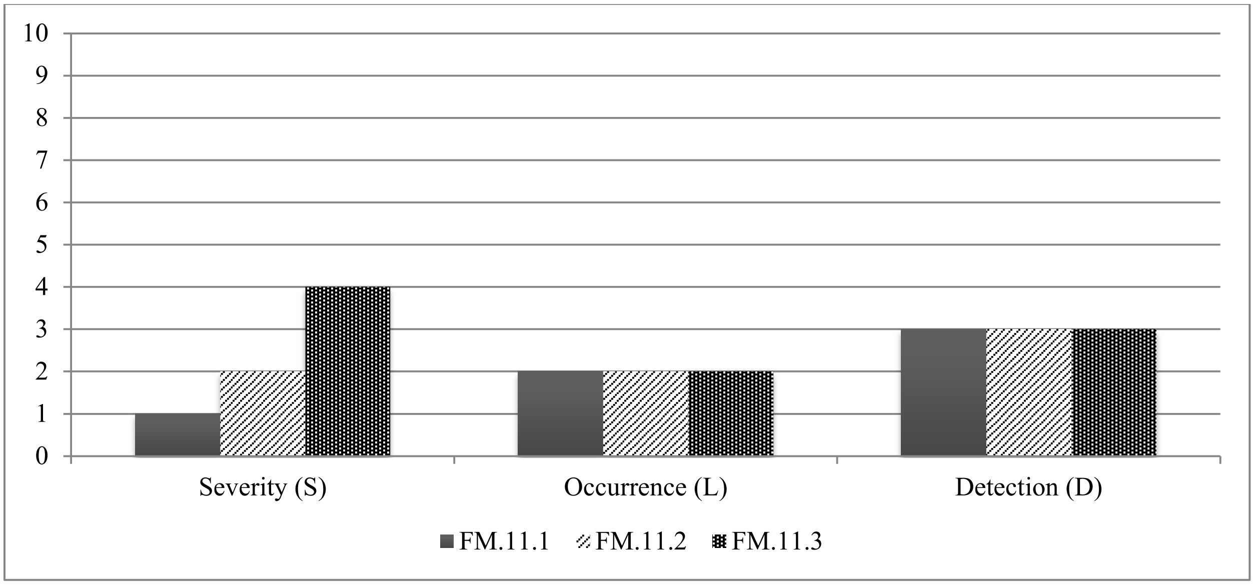

Figure 33. Failure Mode Ranking Numbers – Bill of Materials

4.3.16. FMEA for 50.59/72.48 Review

As described in Section 4.2.14, a 50.59/72.48 review is an evaluation of a plant's licensing documentation. Therefore, errors in this review can lead to regulatory issues. For a design project, issues with the 50.59/72.48 review can lead to problems in future design phases. During the development of a conceptual design this review is preliminary; therefore, changes are expected to occur during later phases. Two failure modes were identified for this activity. These are:

- FM.12.1 – Originators are not qualified to perform 50.59/72.48 review;
- FM.12.2 – Review was not performed correctly.

Table 40 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 41 and Figure 34. The FMEA table shows both failure modes as having the same impact on the project.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
50.59/72.48 Review	FM.12.1	50.59/72.48 review might not fulfil customer's requirements	Qualified resources may not have been available to perform task	Project Planning Questioning Attitude	Always ensure that assigned individuals are qualified under the process they are working on.
	FM.12.2	Additional effort might need to be added to later design phases	Individuals may not have been familiar with the plant's process or the system/component evaluated	Validate Assumptions Self-Checking Peer Review	Individuals should ensure they are knowledgeable on a topic before accepting to perform work.

Table 40. Failure Modes, Effects, Causes, and Recommendations – 50.59/72.48 Review

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
50.59/72.48 Review	FM.12.1	6	2	3	36
	FM.12.2	6	2	3	36

Table 41. Failure Mode Ranking Numbers – 50.59/72.48 Review

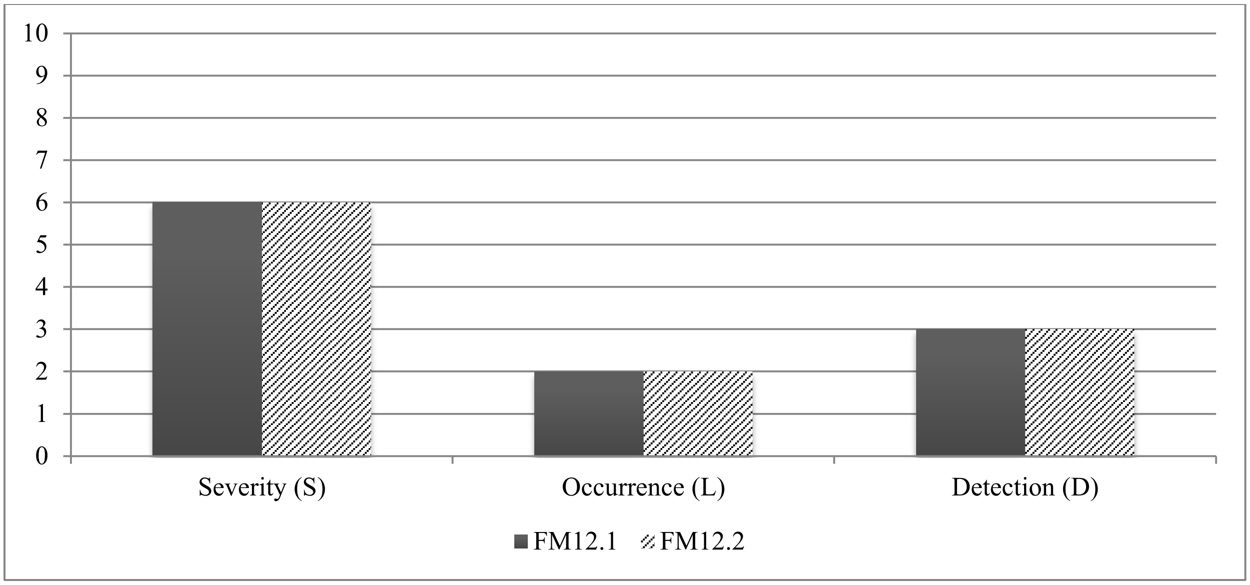

Figure 34. Failure Mode Ranking Numbers – 50.59/72.48 Review

4.3.17. FMEA for SAR Update

The update of a plant's Safety Analysis Report (SAR) is a result of the 50.59/72.48 review. The severity of not updating the Safety Analysis Report (SAR) correctly, after the final design is complete, can result in licensing issues for the plant. Since the changes identified during the conceptual design review are preliminary, the severity during this phase is not as significant. Only one failure mode was identified for this activity:

- FM.13.1 – Not all affected sections and/or figures were identified.

Table 42 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 43 and Figure 35.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
SAR Update	FM.13.1	Information may be left out of SAR, or SAR may contain outdated information.	A proper review of the SAR may not have been performed.	Questioning Attitude Validate Assumptions Peer Review	When unsure, always consult the Licensing Department. During stakeholder reviews, ensure the Licensing stakeholder provides comments or recommendations for improvement.

Table 42. Failure Modes, Effects, Causes, and Recommendations – SAR Update

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
SAR Update	FM.13.1	4	2	3	24

Table 43. Failure Mode Ranking Numbers – SAR Update

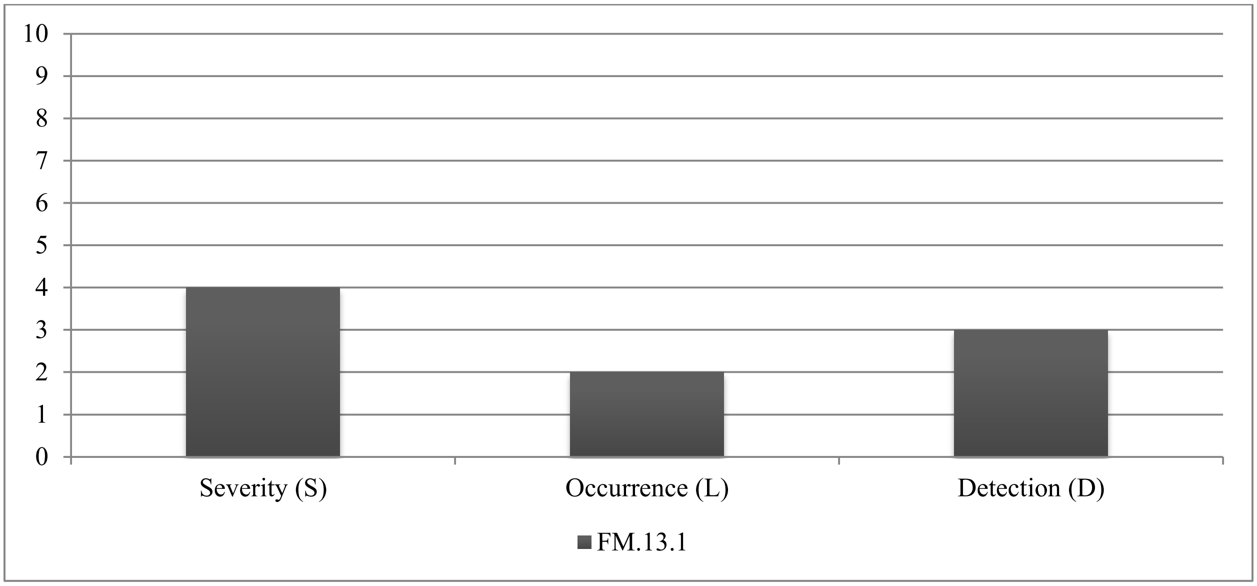

Figure 35. Failure Mode Ranking Numbers – SAR Update

4.3.18. FMEA for Programs Impact Review

The programs impact review performed during the conceptual design phase of a project is preliminary, but this does not mean that issues with this review are insignificant. The programs impact review typically evaluates a program and also identifies any documents that would need to be updated as a result of the implementation of the new design. An example of this is the Fire Protection Program. As part of this program's review engineers need to identify if the amounts of flammable sources in a specific room would be affected. Typically this information is captured in a calculation, which at the same time determines the design of the fire protection system within the specific room. If the preliminary review of this program fails to identify the impact of the new design, this could result in significant rework during future design phases. This rework could cause changes in schedule and even deliverables. Two failure modes were identified for this activity. These are:

- FM.14.1 – Not all impacted programs are identified;
- FM.14.2 – Impacted programs are not properly evaluated.

Table 44 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 45 and Figure 36. The FMEA table shows both failure modes as having the same impact on the project.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Programs Impact Review	FM.14.1	Impacted programs will need to be identified during later design phases	Engineers are not familiar with the plant's programs and how they relate to the project's scope	Self-Checking Questioning Attitude Validate Assumptions Peer Review	Ensure engineers and SME reviewers are familiar with the scope of the project and the potential impacted plant programs. Discussions with plant program owners may be beneficial.
		Additional impacted documents and calculations might be identified and added to the project's scope			
	FM.14.2	Additional impacted documents and calculations might be identified and added to the project's scope	Engineers are not familiar with the plant's programs and how they relate to the project's scope	Self-Checking Questioning Attitude Validate Assumptions Peer Review	Ensure engineers and SME reviewers are familiar with the scope of the project and the potential impacted plant programs. Discussions with plant program owners may be beneficial.

Table 44. Failure Modes, Effects, Causes, and Recommendations – Programs Impact Review

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Programs Impact Review	FM.14.1	7	2	3	42
	FM.14.2	7	2	3	42

Table 45. Failure Mode Ranking Numbers – Programs Impact Review

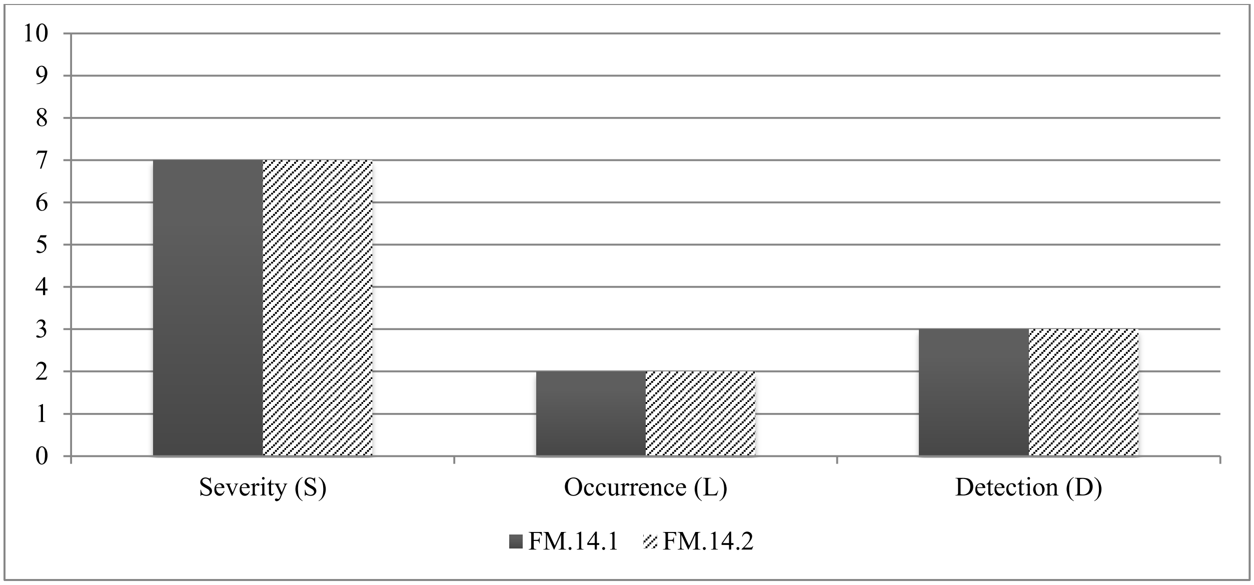

Figure 36. Failure Mode Ranking Numbers – Programs Impact Review

4.3.19. FMEA for SME Internal Review

The SME internal review is the last control to detect issues with a design package. This analysis identified two failure modes for this activity. These are:

- FM.15.1 – SME is not qualified to perform the review;
- FM.15.2 – Review identified issues with the content of the package.

Table 46 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. SMEs perform this activity. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 47 and Figure 37. The FMEA table shows FM.15.2, review identified major issues with the content of the package, as being the most significant issue that could affect this activity.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
SME Internal Review	FM.15.1	Design package might not fulfil customer's requirements	Qualified resources may not have been available to perform the task	Project Planning	Always ensure assigned individuals are qualified under the process they are working on.
	FM.15.2	Design package might not be ready to be submitted to the customer	Resource engineers might not have been the correct individuals to perform the work Peer reviews failed to identify errors	Questioning Attitude Validate Assumptions Peer Review Product Review Meeting	Enough time should be allotted to SME reviews to allow for a thorough and high quality review of design packages.

Table 46. Failure Modes, Effects, Causes, and Recommendations – SME Internal Review

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
SME Internal Review	FM.15.1	4	1	2	8
	FM.15.2	6	1	2	12

Table 47. Failure Mode Ranking Numbers – SME Internal Review

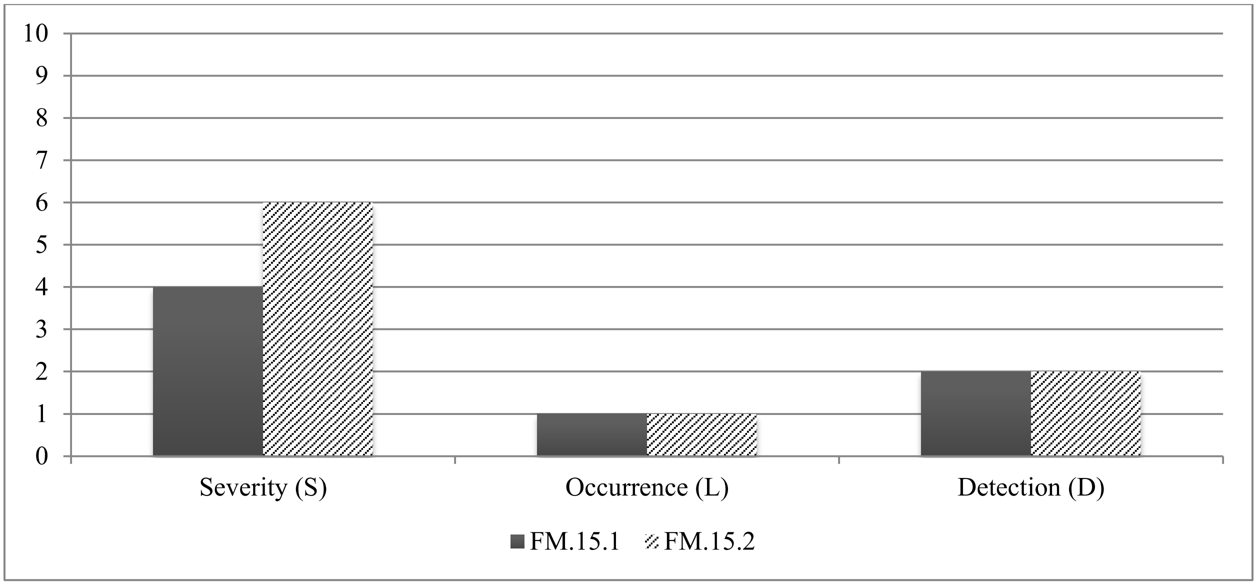

Figure 37. Failure Mode Ranking Numbers – SME Internal Review

4.3.20. FMEA for Next Phase Estimate

The creation of an estimate and schedule for future design phases is one of the most important activities that can be performed during the conceptual design phase, other than the development of the design itself. This activity will determine the structure of the remainder of the project. Errors in estimate or schedule could affect the outcome of the entire project. Five failure modes were identified for this activity. These are:

- FM.16.1 – Person-hour estimate is over or underestimated;
- FM.16.2 – Scope changes from the customer;
- FM.16.3 – Person-hour estimate not accepted by the customer;
- FM.16.4 – Schedule not accepted by the customer;
- FM.16.5 – Estimate did not consider all activities to be completed.

Table 48 describes the potential effect of failure, potential cause(s) of failure, INPO HU tools identified for each failure mode, and recommended actions. The responsible and resource engineers perform this activity. The customer controls some of the failure modes identified. Because of this, a detection rating of 7 was assigned to these. The severity, occurrence, and detection ratings for the failure modes identified are shown in Table 49 and Figure 38. The FMEA table shows FM.16.2 as being the most significant issue that could affect this activity and the entire project.

Function/ Process	Potential Failure Modes	Potential Effects of Failure	Potential Cause(s) of Failure	INPO HU Tools (Prevent and Detect)	Recommended Action(s)
Next Phase Estimate/ Schedule	FM.16.1	Scope of later design phases was not correctly defined	Engineers were not familiar with the scope and/or did not identify all affected documents	Self-Checking Peer Review Project Planning	Always ensure that estimates and schedules are reviewed by the project managers and/or other leaders.
	FM.16.2	Significant changes in design	Changes in the customer's scope or changes in the industry	No controls are in place.	Ensure the design team is constantly communicating with the customer to identify issues early in the project.
	FM.16.3	Rework or complete stop of project	Engineers were not familiar with the scope	No controls are in place.	
	FM.16.4	Rework or complete stop of project	Proposed schedule does not fit customer's implementation plans	No controls are in place.	
	FM.16.5	Scope of later design phases was not correctly defined	Engineers were not familiar with the scope and/or did not identify all affected documents	Project Planning Peer Review Product Review Meeting	Always ensure that estimates and schedules are reviewed by the project managers and/or other leaders.

Table 48. Failure Modes, Effects, Causes, and Recommendations – Next Phase Estimate/Schedule

Function/ Process	Potential Failure Modes	Severity (S)	Occurrence Rating (L)	Detection Rating (D)	RPN (LxSxD)
Next Phase Estimate/ Schedule	FM.16.1	4	2	3	24
	FM.16.2	9	2	7	126
	FM.16.3	4	2	7	56
	FM.16.4	4	2	7	56
	FM.16.5	5	2	3	30

Table 49. Failure Mode Ranking Numbers – Next Phase Estimate/Schedule

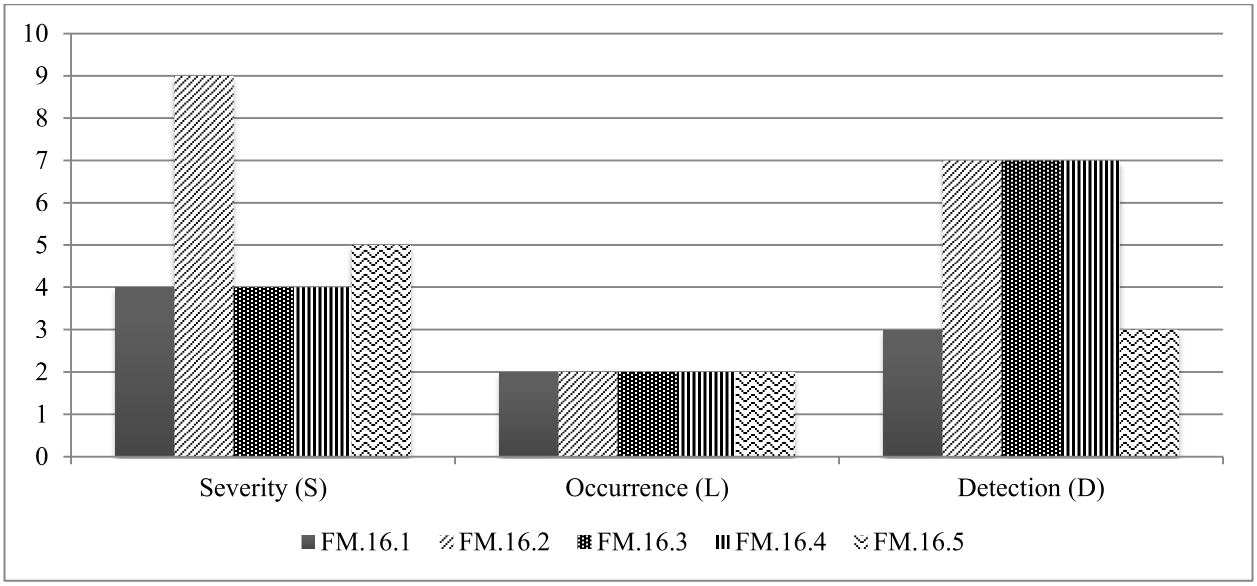

Figure 38. Failure Mode Ranking Numbers – Next Phase Estimate/Schedule

4.3.21. FMEA Conceptual Design Meeting

No FMEA was performed for this activity. The purpose of this meeting is to present the developed conceptual design to plant stakeholders. No specific activities would be performed by engineers or SMEs other than providing a presentation.

4.3.23. Risk Priority Number

As described previously, the RPN is a numerical ranking of the risk of each potential failure mode/cause, made up of the arithmetic product of the three elements: severity of the effect, the likelihood of occurrence of the cause, and the likelihood of detection of the cause (Carlson, 2014). Figure 39 shows the RPN calculated for each activity under this FMEA. The figure shows FM.16.2, "scope changes from the customer," as being the most significant failure mode for this design project. Changes in scope by the customer are not detectable. Sometimes, if the changes are based on regulatory initiatives, they could be anticipated to some extent. A change in scope after a conceptual design has been developed can have a significant impact on project cost, schedule, implementation, and even on outage schedule.

The purpose of comparing the RPN of each activity is to create a sense of significance among all the failure modes identified. Other than identifying FM.16.2 as the most significant, the RPN graph can give the project team a tool that can be used to prioritize mitigation strategies for each failure mode. This graph is a representation of INPOs Principle for Excellence in Integrated Risk Management #5.

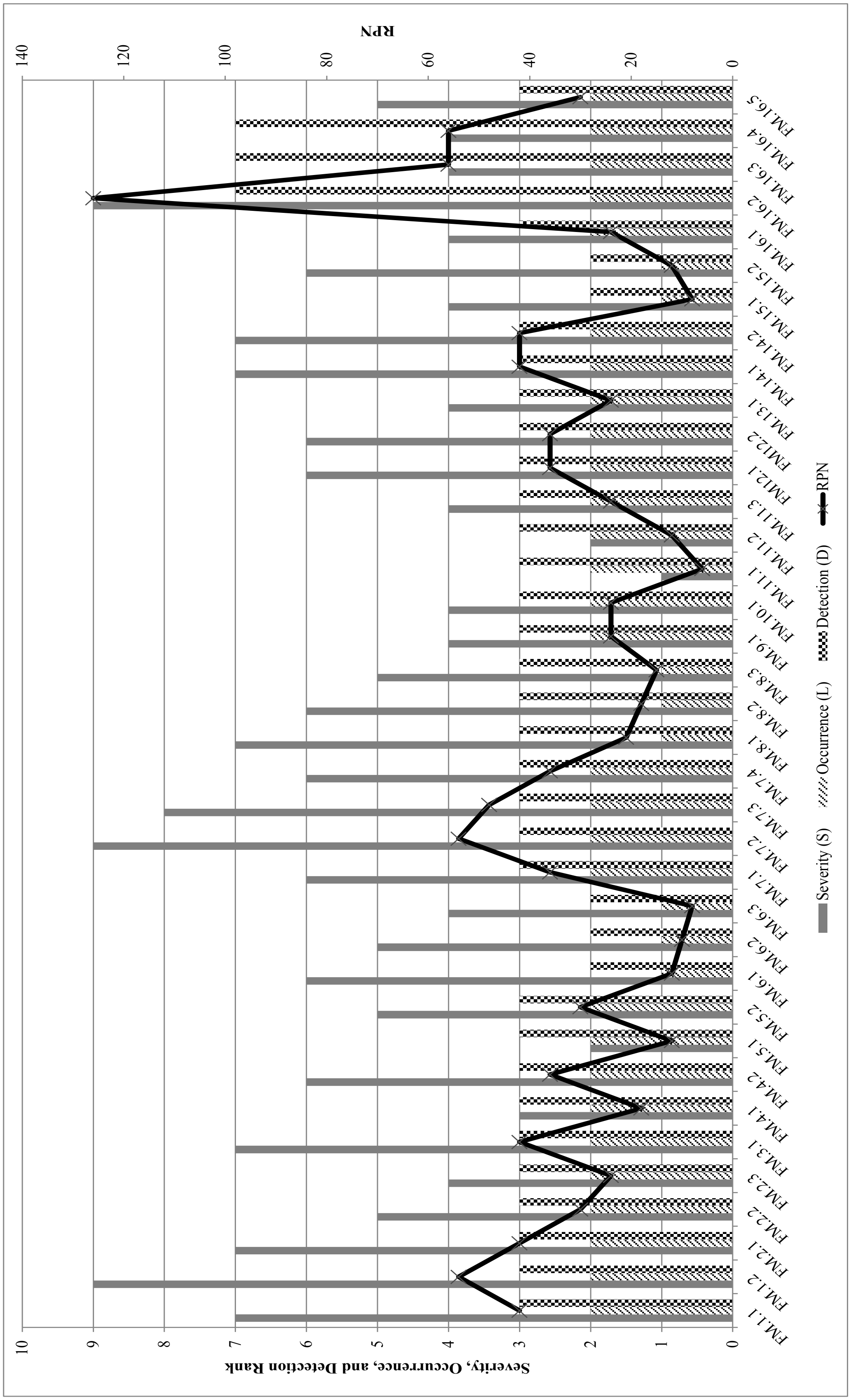

Figure 39. Failure Modes Severity, Occurrence, Detection Ranks, and Risk Priority Number

CHAPTER 5

CONCLUSIONS

The introduction to this dissertation presented the background of engineering design modification projects in the U.S. nuclear power industry, along with this dissertation's problem statement. Various questions were formulated as part of the research, which is addressed as a case study focused on a hypothetical scope. Topics related to the development of engineering design modification projects were discussed as part of the literature review, followed by the research methodology. The results of the research were divided into three parts and comprised the core of this case study. Part one (i.e., Section 4.1) developed a work breakdown structure (WBS) for a design modification project. Part two (i.e., Section 4.2) provided descriptions for activities to be completed as part of a conceptual design package, estimated person-hours, and proposed duration for each activity. Part three (i.e., Section 4.3) comprised a risk analysis using the Failure Modes and Effects (FMEA) tool. This section summarizes the conclusions from this case study. The limitations of the study, recommendations for future research, and contribution to the Engineering Management field of knowledge are also addressed.

5.1. Conclusions and Recommendations

This dissertation formulated three fundamental research questions to be addressed as part of the case study presented here:

- Research Question #1 – How does a comprehensive work breakdown structure for an engineering design project within the nuclear industry look like?
- Research Question #2 – What should take place to deliver a successful project?

- Research Question #3 – What kind of risk could I face? What risk response can be identified? How can these risks impact the overall success of the project?

Research question #1 was answered in Part I of the research results. In this section, a WBS for a design modification project was presented. Representations of the WBS were presented in Figure 13 thru Figure 18. These diagrams help the reader visualize the process. The activities listed in the WBS ranged from the definition of the project scope up to close-out of the design package. The WBS revealed that the activities involved in this type of nuclear project could be widespread with some of the activities, such as the 50.59/72.48 review, being unique to the nuclear industry. These activities are considered part of a detailed design project under the SDP. Various activities were identified within the WBS as being needed to develop a conceptual design. The identified activities are discussed in section 4.2 of the dissertation, which leads to the answer to research question #2.

The discussion presented in Part II answered research question #2. This section provided steps recommended to perform each of the activities successfully. Even though the processes discussed should be captured in plant procedures, the descriptions provided in Section 4.2 also include insights from SME experience, which are typically not recorded in plant procedures. NEI's SDP was referenced throughout the section. Each activity discussed was assigned person-hour estimates and durations. These estimates were developed in response to the pre-determined scope of the case study. The results from Part I were captured in Table 14. This table includes the person-hours assigned to each activity under the responsible resource. This analysis resulted in a total of 679 hours needed to complete the technical portion of a conceptual design package. The information presented in this table was then incorporated into the Microsoft Project software.

The resulting Gantt chart is shown in Figure 21 and Figure 22. The activities described in this section are evaluated for risk in Part III.

Research question #3 was answered in Part III of the research results. This section evaluated each of the activities described in Part II using the Failure Modes and Effects Analysis (FMEA) tool. The process consisted of identifying failure modes for each activity. Each failure mode was then evaluated to determine the potential effects and causes of the failure. INPO human performance tools were assigned to each failure mode. These tools can be used to prevent or detect the failures. Recommended actions to address or mitigate the failure were also provided. The results of each activity-specific FMEA were captured in separate tables. Finally, each failure mode was assigned a severity, occurrence, and detection rating. The criteria for each scale were described in Table 15, Table 16, and Table 17. These ranks were used to calculate the risk priority number (RPN). The results from the scale assignment were also captured in separate tables. A chart was included to provide a graphical representation of the results. Among all the activities described, a total of 37 failure modes were identified and evaluated. The results of the overall FMEA were recorded in Figure 39. This chart gives a graphical representation of the risks that can be expected for each failure mode. Failure mode FM.16.2, “scope changes from the customer,” corresponding to the “Next Phase Estimate” activity, had the highest priority number. This result is mainly due to its high severity and detection ranking. The presence of this failure could cause a significant amount of rework or even the termination of the project. Therefore, engineers and project managers should pay close attention when performing estimates for later design phases.

The activities described and evaluated under this case study are assumed to be performed under a plant-specific quality assurance (QA) program, such as ASME’s NQA-1 (i.e., American

Society of Mechanical Engineers' Nuclear Quality Certification). This QA program governs the procedures under which the work is being performed. Some of these plant-specific procedures address risks such as the ones identified in Section 4.3 but are typically intended for work performed for safety-related structures, systems, and components. This dissertation narrows the gap between risk analysis for safety-related and non-nuclear safety-related work. The results presented in this paper are expected to assist the U.S. nuclear industry in the identification and mitigation of risks beyond what is already addressed in plant-specific procedures.

The results from this dissertation shall be applied to the development of an engineering design modification project iteratively. The recommended actions from the FMEA shall be used to adjust activities in the WBS. These actions can also be used to improve estimated person-hour and durations for each activity, assign more resources, and change the scope of reviews. Overall, this case study can support engineers and projects managers in the development of successful projects as a supplement to plant-specific processes and procedures.

5.2. Limitations and Future Research

The results of this case study are built upon a hypothetical scope for a U.S. nuclear power plant. The person-hour estimates and activity durations provided are limited to a conceptual design performed under the Standard Design Process (SDP). The literature review presented in this dissertation discussed the subject of multi-unit risk. A risk analysis was not performed to address this topic since the case study focuses on a design modification to be implemented at a single-unit nuclear power plant.

The SDP addresses multi-unit matters through the development of a common design package, listed in Figure 19. The common design process initiates after a conceptual design is developed that contains nuclear fleet-level designs and evaluations that are applicable to more than one nuclear site (SDPSC, 2017). The development of an additional risk assessment, along with a risk mitigation plan, is a step in the common design process. The risk assessment to address multi-unit risk could be the basis for future research and could further expand the Engineering Management field of knowledge.

5.3. Contribution to the Engineering Management Field of Knowledge

The nuclear energy industry is a unique business that relies on the knowledge and experience of individuals. Although nuclear power plants utilize countless procedures to perform day-to-day activities, the procedures themselves do not capture essential processes set forth from experience. With an aging workforce and a large percentage of the nuclear workforce approaching retirement, it is up to the new generation to gain this knowledge to move the industry forward. One of the ways this can be achieved is by implementing design modifications.

Design modifications are engineering projects that involve technical problem solving along with the management of engineering processes. The development of a case study that describes in detail the process of developing engineering projects for nuclear power plants is a step towards the documentation of the knowledge needed to successfully develop a design modification.

Old Dominion University (ODU) defines Engineering Management as a specialized form of management that is concerned with the application of engineering principles to business practice (2017). It also states that the discipline addresses the problems, design, and management of projects and complex operations (ODU, 2017). This definition accurately describes the foundation of this research as it applies to engineering projects in the nuclear industry. Therefore, this research will contribute to the Engineering Management field of knowledge by providing a source of detailed information that can be used as a guide when developing engineering projects for nuclear power plants.

REFERENCES

American Society of Mechanical Engineers (ASME). (1974). Quality Assurance Requirements for the Design of Nuclear Power Plants. ANSI N45.2.11. 1974 Edition, June 6, 1974. New York, NY.

Boring, R. L. (2010). Bridging Resilience Engineering and Human Reliability Analysis. INL/CON-10-18621, Idaho National Laboratory

Carlson, C.S. (2014). Understanding and Applying the Fundamentals of FMEAs. 2014 Reliability and Maintainability Symposium, January, 2014.

Dalziell, E.P., McManus, S.T. (2004). Resilience, Vulnerability, and Adaptive Capacity: Implications for System Performance. Stoos, Switzerland: 1st International Forum for Engineering Decision Making (IFED), 5-8 Dec 2004.

Davenport, T.H. (2005). Thinking for a Living: How to Get Better Performance and Results from Knowledge Workers. Harvard Business School Press, Boston, Massachusetts.

Heo, G., Kim, M. C., Yoon, J. W., Kim, I. S., and Jae, M. (2016). Gap Analysis Between Single-Unit and Multi-Unit PSAs for Korean NPPs. 13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13). Seoul, Korea.

Huber, S., van Hijgerden, I., de Witt, A., W.A. Dekker, S. (2008). Learning from Organizational Incidents: Resilience Engineering for High Risk Process Environments. Process Safety Progress, Volume 28, Issue 1. Wiley InterScience.

Institute of Nuclear Power Operations (INPO). (2015). Conduct of Engineering Programs at Nuclear Power Stations. INPO 15-003, Revision 0, April 2015. Atlanta, GA.

Institute of Nuclear Power Operations. (2006). Human Performance Reference Manual. INPO 06-003, Atlanta, GA. Retrieved from: http://www.inpo.org/Library/INPODocs/2006/06-003/06-003.pdf

Institute of Nuclear Power Operations. (2007). Human Performance Tools for Engineers and Other Knowledge Workers: Practices for Anticipating, Preventing, and Catching In-Process Errors. INPO 05-002, Revision 1. Atlanta, GA. Retrieved from: https://web.inpo.org/Good%20Practices/INPO05-002.pdf

Institute of Nuclear Power Operations. (2015). Principles for Excellence in Integrated Risk Management. INPO 15-011, Atlanta, GA.

Institute of Nuclear Power Operations. (2017). Our History. Retrieved from: http://www.inpo.info/AboutUs.htm#history

International Atomic Energy Agency. (2004). The nuclear power industry's ageing workforce: Transfer of knowledge to the next generation. IAEA-TECDOC-1399, June 2004.

Kim, I. S., Jang, M., and Kim, S. R. (2016). Holistic Approach to Multi-Unit Site Risk Assessment: Status and Issues++. 13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13). Seoul, Korea.

Kinsella, W. (2012). Environments, Risks, and the Limits of Representation: Examples from Nuclear Energy and Some Implications of Fukushima. Environmental Communication, Volume 6, Number 2, June 2012, pp. 251 – 259.

McManus, S., Seville, E., Vargo, J., and Brunsdon, D. (2008). Facilitated Process for Improving Organizational Resilience. Natural Hazards Review, Volume 9, Issue 2, (pp. 81–90).

National Oceanic and Atmospheric Administration. (2017). Great Tohoku, Japan Earthquake and Tsunami, 11 March 2011. Retrieved from: https://ngdc.noaa.gov/hazard/11mar2011.html

Newberry, S.F. and Kuo, P.T. (1998). Regulatory perspective of license renewal, Nuclear Engineering and Design, Volume 181, pp. 447-450. Elsevier.

Nguyen, T.-H., Marmier, F., and Gourc, D. (2013). A decision-making tool to maximize chances of meeting project commitments. Int. J. Production Economics, Volume 142, pp. 214 – 224.

Nuclear Energy Agency (NEA) and Organisation for Economic Co-operation and Development (OECD) (2002). Chernobyl: Assessment of Radiological and Health Impacts. Retrieved from: https://www.oecd-nea.org/rp/chernobyl/chernobyl-figure2.pdf

Nuclear Energy Institute (2016). Delivering the Nuclear Promise®: Advancing Safety, Reliability and Economic Performance. Retrieved from: https://www.nei.org/CorporateSite/media/filefolder/Communication-Tools/Delivering%20the%20Nuclear%20Promise/Strategic-Plan_Delivering-The-Promise_r1_rtm.pdf?ext=.pdf

Nuclear Energy Institute (2017). Delivering the Nuclear Promise. Retrieved from: https://www.nei.org/Issues-Policy/Delivering-the-Nuclear-Promise

Nuclear Energy Institute (2017). Implement Standard Design Change Process. Efficiency Bulletin: 17-06. March 6, 2017. Retrieved from: https://www.nei.org/CorporateSite/media/filefolder/Delivering%20the%20Nuclear%20Promise/Efficiency%20Bulletins/2017/EB-17-06-(ENG-003)-Implement-Standard-Design-Change-Process-final.pdf?ext=.pdf

Nuclear Energy Institute (NEI). (2005). Industry Guideline For Implementing The Requirements of 10 CFR Part 54 – The License Renewal Rule. Revision 6, June 2005.

Nuclear Regulatory Commission (2005). Good Practices for Implementing Human Reliability Analysis (HRA). (Document No. NUREG-1792). Washington, DC: Author. Retrieved from: http://pbadupws.nrc.gov/docs/ML0511/ML051160213.pdf

Nuclear Regulatory Commission (2014). Backgrounder on Chernobyl Nuclear Power Plant Accident. Retrieved from: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/chernobyl-bg.html

Nuclear Regulatory Commission (2014). Backgrounder on the Three Mile Island Accident. Retrieved from: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html#impact

Nuclear Regulatory Commission (2017). 10 CFR Part 54; Requirements for Renewal of Operating Licenses for Nuclear Power Plants. Retrieved from: https://www.nrc.gov/reading-rm/doc-collections/cfr/part054/index.html

Nuclear Regulatory Commission (2017). 10 CFR 50.34; Contents of applications; technical information. Retrieved from: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0034.html

Nuclear Regulatory Commission (2017). List of Power Reactor Units. Retrieved from: https://www.nrc.gov/reactors/operating/list-power-reactor-units.html

Nuclear Regulatory Commission (2017). Map of Power Reactor Sites. Retrieved from: https://www.nrc.gov/reactors/operating/map-power-reactors.html

Nuclear Regulatory Commission (2017). Part 54 – Requirements for Renewal of Operating Licenses for Nuclear Power Plants. Retrieved from: https://www.nrc.gov/reading-rm/doc-collections/cfr/part054/full-text.html

Nuclear Regulatory Commission (2017). Power Reactors. Retrieved from: http://www.nrc.gov/reactors/power.html

Old Dominion University (2017). Engineering Management and Systems Engineering. Retrieved from: https://www.odu.edu/emse#.WNh7HmdMqHs

Pollack, J. (2012). Transferring knowledge about knowledge management: Implementation of a complex organizational change programme. International Journal of Project Management, Volume 30, (pp. 877-886).

Standard Design Process Steering Committee. (2017). Standard Design Process. IP-ENG-001, Revision 0, February 2017.

The Federation of Electric Power Companies of Japan (FEPC) (2018). Outline of the Accident at the Fukushima Daiichi Nuclear Power Station. Retrieved from: http://www.fepc.or.jp/english/nuclear/power_generation/overview/sw_overview_03/index.html

Weinberg, A.M. (2004). On “immortal” nuclear power plants. Technology in Society, Volume 26, pp. 447-453. Elsevier.

Yanev, Y. (2013). The challenge of managing knowledge in nuclear energy development. Energy Strategy Reviews, Volume 1, (pp. 282-285).

APPENDIX A

The following table is a list of all nuclear power reactors licensed in the U.S. Each plant/unit is identified by type, PWR or BRW. Status of License Renewal application is also shown.

#	Plant Name and Unit	PWR	BWR	License Renewal Application Status
1	Arkansas Nuclear 1	×		Complete
2	Arkansas Nuclear 2	×		Complete
3	Beaver Valley 1	×		Complete
4	Beaver Valley 2	×		Complete
5	Braidwood 1	×		Complete
6	Braidwood 2	×		Complete
7	Browns Ferry 1		×	Complete
8	Browns Ferry 2		×	Complete
9	Browns Ferry 3		×	Complete
10	Brunswick 1		×	Complete
11	Brunswick 2		×	Complete
12	Byron 1	×		Complete
13	Byron 2	×		Complete
14	Callaway	×		Complete
15	Calvert Cliffs 1	×		Complete
16	Calvert Cliffs 2	×		Complete
17	Catawba 1	×		Complete
18	Catawba 2	×		Complete
19	Clinton		×	To be submitted in 2017
20	Columbia Generating Station		×	Complete
21	Comanche Peak 1	×		To be submitted in 2022
22	Comanche Peak 2	×		To be submitted in 2022
23	Cooper		×	Complete
24	D.C. Cook 1	×		Complete

Table 50. List of Power Reactors in the U.S. and Application Status (NRC, 2018)

#	Plant Name and Unit	PWR	BWR	License Renewal Application Status
25	D.C. Cook 2	×		Complete
26	Davis-Besse	×		Complete
27	Diablo Canyon 1	×		Under Review
28	Diablo Canyon 2	×		Under Review
29	Dresden 2		×	Complete
30	Dresden 3		×	Complete
31	Duane Arnold		×	Complete
32	Farley 1	×		Complete
33	Farley 2	×		Complete
34	Fermi 2		×	Complete
35	FitzPatrick		×	Complete
36	Ginna	×		Complete
37	Grand Gulf 1		×	Complete
38	Hatch 1		×	Complete
39	Hatch 2		×	Complete
40	Hope Creek 1		×	Complete
41	Indian Point 2	×		Under Review
42	Indian Point 3	×		Under Review
43	La Salle 1		×	Complete
44	La Salle 2		×	Complete
45	Limerick 1		×	Complete
46	Limerick 2		×	Complete
47	McGuire 1	×		Complete
48	McGuire 2	×		Complete
49	Millstone 2	×		Complete

Table 50. Continued

#	Plant Name and Unit	PWR	BWR	License Renewal Application Status
50	Millstone 3	×		Complete
51	Monticello		×	Complete
52	Nine Mile Point 1		×	Complete
53	Nine Mile Point 2		×	Complete
54	North Anna 1	×		Complete
55	North Anna 2	×		Complete
56	Oconee 1	×		Complete
57	Oconee 2	×		Complete
58	Oconee 3	×		Complete
59	Oyster Creek		×	Complete
60	Palisades	×		Complete
61	Palo Verde 1	×		Complete
62	Palo Verde 2	×		Complete
63	Palo Verde 3	×		Complete
64	Peach Bottom 2		×	Complete
65	Peach Bottom 3		×	Complete
66	Perry 1		×	To be submitted in 2019
67	Pilgrim 1		×	Complete
68	Point Beach 1	×		Complete
69	Point Beach 2	×		Complete
70	Prairie Island 1	×		Complete
71	Prairie Island 2	×		Complete
72	Quad Cities 1		×	Complete
73	Quad Cities 2		×	Complete
74	River Bend 1		×	To be submitted in 2017

Table 50. Continued

#	Plant Name and Unit	PWR	BWR	License Renewal Application Status
75	Robinson 2	×		Complete
76	Saint Lucie 1	×		Complete
77	Saint Lucie 2	×		Complete
78	Salem 1	×		Complete
79	Salem 2	×		Complete
80	Seabrook 1	×		Under Review
81	Sequoyah 1	×		Complete
82	Sequoyah 2	×		Complete
83	Shearon Harris 1	×		Complete
84	South Texas 1	×		Under Review
85	South Texas 2	×		Under Review
86	Summer	×		Complete
87	Surry 1	×		Complete
88	Surry 2	×		Complete
89	Susquehanna 1		×	Complete
90	Susquehanna 2		×	Complete
91	Three Mile Island 1	×		Complete
92	Turkey Point 3	×		Complete
93	Turkey Point 4	×		Complete
94	Vogtle 1	×		Complete
95	Vogtle 2	×		Complete
96	Waterford 3	×		Under Review
97	Watts Bar 1	×		No intent yet; expires 2035
98	Watts Bar 2	×		No intent yet; expires 2055
99	Wolf Creek 1	×		Complete

Table 50. Continued

Reactor Type	Number of Reactor Units
PWR	66
BWR	34

Table 51. Summary of Reactors in the U.S.

License Renewal Application Status	Number of Reactor Units
Completed	84
Under Review	8
Future Submittal	5
No Intent to Submit Yet	2

Table 52. Summary of License Renewal Application Status for Reactors in the U.S.

APPENDIX B

Part I Subject Matter Expert (SME) Review

SME: #1
SME Title: Project Engineer Electrical/I&C
Description of SME Experience: 35+ Years of Engineering and Engineering Management experience on power plant projects, including nuclear and non-nuclear projects.
Scope: *Review Part I of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
Chapter 4, Lead-in paragraph	Providing recommended person-hour estimates may be difficult unless you have SME's from all disciplines and your input is not all from WEC. If your input was solely based on information from WEC sources, I can foresee some WEC legal type not being too thrilled. (i.e., they may consider it to be proprietary)	The recommended person-hour estimates are based on own experience from current and previous positions.
4.1	Should you clarify that the list is the WBS for Engineering only? The other groups will also have WBS's which you have only partially touched on.	Added “from the Engineering perspective”.
1.1.3	Maybe add Architectural, Geotechnical. Should you be adding other department scopes, such as QA, Procurement, Construction, Startup/Commissioning, Customers/Owner's Scope. Understanding these groups scopes (ie, the DOR between these groups and Engineering) will help define deliverables and associated WBS needs.	These disciplines follow the SDP, identified in IP-ENG-001, Attachment 10.

Table 53. Part I SME #1 Comments and Resolutions

Section/Table/Figure	Comment/Recommendation	Resolution
1.1.4	Maybe indicate "Proposed Design Change/Problem Resolution" Also, I think this should be listed ahead of the Project Scope. Unless, this is meant to be the "Detailed Project Scope".	Changed to "Proposed Design Change/Problem Resolution."
1.1	Suggest adding a section on defining resources needed versus resources available. Performing skills gap analysis and making decisions to self-perform engineering or sub-contracting out the work to third parties who already possess the necessary skills. By defining what will be self-performed and what will be sub-contracted will in turn define what activates to include in the WBS.	Added new 1.1.3 for identifying resources needed.
1.1.5	Suggest listing the different types of design input: Existing plant licensing and design information; New Design Functional and Performance Criteria; Regulatory Requirements; Design Codes and Standards; Customer/Owner's operations and maintenance criteria; Commissioning and Testing features to be incorporated into the design; physical layout and spatial criteria; engineering discipline department standards and guidelines; Owner preferred supplier information,. You could expand the list further.	This is explained in Section 4.2 and references the programs identified in the SPD.
	If you want to, you could further identify design inputs associated with every program the Customer/Owner has. (e.g, Fire protection, MOVs, EQ, Seismic, etc)	

Table 53. Continued

Section/Table/Figure	Comment/Recommendation	Resolution
	The exercise of defining all of the design inputs helps define the design outputs needed for the Project.	
1.2.1	This is item 1.1.5. Do you need to repeat here?	The purpose of the repeat is to ensure that the responsible engineer is constantly communicating with the customer's design engineering group.
1.2.4	General comment: It will be difficult to provide meaningful engineering rates without identifying the specific documents that each discipline works with.	Those details are shown in section 4.2 where a specific scope of work is provided, including documents to be created or updated.
1.2.1.2, 1.2.2.2, etc (Numbering needs to be reviewed/corrected; these numbers should be 1.2.4.2, 1.2.5.2, etc)	Is this meant to include all reviews, including customer reviews? General question applicable to all documents listed. See comment against 1.6.1	Yes, but mainly aimed at reviews/verifications performed by the firm, which will be estimated in Section 4.2 for a specific work scope. Numbering has been updated.
1.2.8.1 (Same comment for numbering as above)	Do you want to list some of these other documents: Equipment Data Sheets, Motor Data Sheets, Instrument Data Sheets. equipment lists, electrical load lists, instrument lists, cable and raceway lists, cable connection lists, pipe and valve lists, pipe hangar lists, EQ equipment lists; Equipment supplier documents, engineering service supplier documents; BOMs. The above could be condensed in generic categories of Data Sheets, Component Lists, Supplier Documents, BOMs.	Added data sheets, components lists, and supplier documents as examples under 1.2.11, other documents.
1.3.2.1	Suggest adding (ie, constructability review)	Added.

Table 53. Continued

Section/Table/Figure	Comment/Recommendation	Resolution
1.3.3.3	Coordinate with Owner as well. Or, is this this just part of the BOM review/approve cycle in 1.2.8.2?	Updated 1.3.3.1 to “obtain input from customer (e.g. procurement, engineering, installing group).”
1.3.4.1	Maybe indicate both Owner's testing group as well as whoever is contracted to perform the testing?	Updated to “Obtain Input from Customer (e.g. test group).”
1.6.1	You have these reviews listed here, but also include them in Section 1.2. Seems redundant.	The reviews listed under 1.2 are for processes outside of the design package. The reviews listed under 1.6.1 are for the design package. Updated 1.6.1 to “Design Package Inter-Discipline Review/Verification.”
1.6.1	Suggest adding "Inter-discipline Reviews."	See previous response.
2	Suggest adding: "Performance test acceptance report reviews."	Added as 2.3.
1.2	It might be better to list all the documents in one section, then list the sequencing of review and processing that is typical for each document. When done this way, you can expand upon the list of reviewer/verifiers instead of in 1.6.1	See response for 1.6.1.

Table 53. Continued

SME: #2	
SME Title: Structural Engineer	
Description of SME Experience: Structural engineer of plant mods at nuclear power plants.	
Scope: *Review Part I of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*	

Section/Table/Figure	Comment/Recommendation	Resolution
4.1 / 1.2.1	This seems to be from the perspective of an outside contractor. Recommend reword to 5 guys meeting or equivalent	Added "Customer's" to specify.
1.2.5.1	Recommend "station" procedures to differentiate between installation procedures	Changed 1.2.8.1 (updated number) to "Update/Generate Administrative and Installation Procedures"
1.2.4 thru 1.2.11	Numbering doesn't match higher tier	Updated numbering.
1.3.2.1	The engineer writes the instructions, may need to add some language, sounds like the installer is doing this. The installer reviews the package, but doesn't write the instructions. Similar for 1.3.3 and 1.3.4	Changed to "Obtain Input from…" on 1.3.2.1, 1.3.3.1, and 1.3.4.1.
1.4.2.1	Typically only updates to the SAR are provided, the station updates the sar all at one time	Changed to "Identify Recommended Changes to the SAR."
1.4.4.1	Update if required, not always required	Changed to "Identify Recommended Changes to the Operating License."
1.6.1.2	Written from an outside firm's perspective, may want to keep it to a station's wbs. An outside firm would be working to an augmented program.	The case study is based on an outside firm doing the work.
1.6.4	Should you add "and get final signatures"? The activities make sense, but may want to show that these are part of the design phase before the package is approved.	Added 1.6.5, "Final signatures and approval."
2.2	Add "minor" changes	Added.
2.3	Return "SSC" to service	Added "SSC."

Table 54. Part I SME #2 Comments and Resolutions

SME: #3
SME Title: Project Manager
Description of SME Experience: Project manager for nuclear plant design modifications with more than 15 years of technical engineering experience.
Scope: *Review Part I of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
Introduction and Literature Review	Editorial comments throughout. Markup provided.	Updated.
WBS 1.4	Do you have to define this or have it more generalized?	Updated.
WBS 1.4.2	Define SAR.	Defined.
WBS 1.6.1.1	Define SME.	Defined.

Table 55. Part I SME #3 Comments and Resolutions

APPENDIX C

Part II Subject Matter Expert (SME) Review

SME: #1
SME Title: Project Engineer Electrical/I&C
Description of SME Experience: 35+ years in engineering, engineering supervision, engineering project management for fossil and nuclear power plant projects.
Scope: *Review Part II of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
Project Definition and Pre-Design Walkdown	This is especially true for non-safety related designs as the plant's configuration control tends to put more focus on the safety-related design.	Agree. Added some explanation.
Project Definition and Pre-Design Walkdown	"Craft" is normally associated with construction personnel. Unless "craft" is a generic term in your writings, suggest that you indicate "plant operations and maintenance personnel". "Craft" could be still considered a stakeholder since they are the customer to engineering's construction design and may have some insight as to constructability issues.	Replaced “craft” with “plant operations and maintenance”.
Project Definition and Pre-Design Walkdown	Do you want to be using a command tense 'shall', instead of a recommendation tense, i.e., 'should' (typical comment)?	Replaced “shall” with “should” in most instances.
Project Definition and Pre-Design Walkdown	Suggest adding: For purposes of this simplified case, It will be assumed that there are no electrical controls and no heat tracing required."	Added.

Table 56. Part II SME #1 Comments and Resolutions

Section/Table/Figure	Comment/Recommendation	Resolution
Project Definition and Pre-Design Walkdown	Suggest adding: "For simplicity, engineering supervision, project management, and other overhead charges will be ignored when developing the estimate. These charges are typically percentages of the direct engineering cost."	Added.
Design Inputs	Does the SDP address schedule? This is what puts the demand on the resources. For example, a modification needing to be incorporated in a future outage will be less demanding than one that needs to be incorporated in the upcoming outage.	The SDP des not specifically discuss this subject.
Design Inputs	Are you adding more here? or should this be "...etc.)"	No. This bullet continues on the next one below.
Design Inputs	Goal of the Conceptual phase should be to take the design from a rough idea to one that has structure and legitimacy. All items potentially having a high risk impact on cost or acceptability should be identified, defined, and incorporated into the conceptual design. Other risks can be cataloged in a risk register with mitigating strategies. Also, the type of documents created during the conceptual phase should be agreed to with the customer. Different customers have different expectations. You could add this to Page 61 discussion where you introduce the conceptual design phase.	Added wording.

Table 56. Continued

Section/Table/Figure	Comment/Recommendation	Resolution
Drawings	Suggest putting this first as all design flows down from key documents. Also, note that in many organizations, the Mechanical Engineers are not the people doing the piping layout. ME's know the mechanical system process information, selection of pipe class, and determination of the sizing. Separate personnel typically do the piping routing, design of pipe supports, and perform the stress analysis. These can be other ME's or Piping designers. C/S Engineers usually only get involved when there is a special attachment to a structure needed, or when a foundation is needed.	Moved item.
Drawings	'Design technician' may be more PC.	Changed “drafter” to “design technician”.
Drawings	Double edge sword. Designers are typically paid less per hour than engineers, particularly Principal engineers. Unless PE has good working cad skills, the task should be left to a design technician. What you generally find is the most senior engineers do not have these skills. I do agree that it should be the company's goal that the young engineers acquire these skills as early in their careers as possible for the reasons you state.	Agree.

Table 56. Continued

Section/Table/Figure	Comment/Recommendation	Resolution
Drawings	And in what format? We have people who know only Microstation and don't know Autocad, and vice-a-versa. This plays into the required skills of the resources and the job-hour estimates.	Added.
Calculations	Change "future" to "later"	Updated.
Specifications	Some amount of time is needed to specify the valve either on a BOM or on a procurement requisition. This detail is likely not important with regards to what you are trying to present, but I felt I should mention.	This information accounted for in the "Bill of materials" section.
Procedures	I note that the procedures here are the plant operating procedures rather than the design change package and supporting document procedures. Maybe clarify?	Updated to "Plant Operating Procedures".
Installation Instructions	YES! I agree 100%. Not recognizing how the design will be tested or commissioned is a major source of under-estimates. Key stakeholders in the conceptual design phase are the construction and commissioning managers.	Agree.

Table 56. Continued

SME: #2
SME Title: Structural Engineer
Description of SME Experience: 15 years of structural design of nuclear facilities
Scope: *Review Part II of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
4.2	2nd paragraph, change "divided in phases" to "divided into phases"	Updated to "into".
Page 61, before bullets	You're jumping right into a project, but it would be helpful to explain the scoping that was already performed. For example, why are they installing the drain line?	Added background information.
Page 62	A more realistic resource allocation would be something less than 100% utilization, possibly 7 hours/day	Changed to 7 hours/day.
Page 62, last paragraph before Pre-Job Brief	Change "As stated in previously" to "As stated previously"	Updated.
Page 63	Typo "led" to "lead"	This is the past tense for lead.
Page 63	Note that procedures are not controlled once printed	Agree.
Page 64	Wouldn't the scope start in the PJB? Then be expanded or confirmed during the walkdown	Added "Pre-job briefs are also an essential activity to perform before walkdowns".
Page 64	Change "contains accurate information" to contains accurate or complete information"	Updated.
Page 66	Change " that under consideration" to "that into consideration"	Updated.
Page 66	Delete "Same applies to any other disciplines", as this is obvious	Deleted.

Table 57. Part II SME #2 Comments and Resolutions

Section/Table/Figure	Comment/Recommendation	Resolution
Page 70 – cad paragraph	I don't agree with using engineers to do drafting; doesn't seem like an efficient use of resources. No change required.	Somewhat agree.
Page 72	Doesn't the pipe support need a calculation?	Added calculation for pipe support, including person-hour estimate.
Page 73 - TR	Change "only add a drain line to FWT" to "only adds a drain line to FWT" Change "assumed that not" to "assumed that no"	Updated.
Page 74	"radioactive area" should be "radiation controlled area"	Updated.

Table 57. Continued

SME: #3
SME Title: Project Manager
Description of SME Experience: Project manager for nuclear plant design modifications with more than 15 years of technical engineering experience.
Scope: *Review Part II of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
Section 4.2	Editorial comments. Markup provided.	Updated.

Table 58. Part II SME #3 Comments and Resolutions

APPENDIX D

Part III Subject Matter Expert (SME) Review

SME: #1
SME Title: Project Engineer Electrical/I&C
Description of SME Experience: 35+ years in engineering, engineering supervision, engineering project management for fossil and nuclear power plant projects.
Scope: *Review Part III of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
All	Editorial comments throughout.	Updated.
4.3.5	Need to identify "FM 1.1" in the writeup. "FM 1.2" is identified, but not FM 1.1	This has been added as part of Chapter 5, under conclusions.
4.3.22	You might want to contrast your conclusions to the QA program and procedures the work is being done under. I think you will find that many of the risks are already addressed by the program and procedures if the design is safety related, but less so for non-safety related work. This gap analysis will help focus on what else should be done to mitigate risk beyond what the current program already addresses.	This has been added as part of Chapter 5, under recommendations.
	Following on from previous comment, do you have any suggestions for the reader on how to deal with the identified risks for this sample project? Should you inflate the budget? Adjust schedule? Get different resources?	Updated.

Table 59. Part III SME #1 Comments and Resolutions

SME: #2

SME Title: Structural Engineer

Description of SME Experience:
Structural engineer of plant mods at nuclear power plants.

Scope: *Review Part III of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
4.3.2	"engineers experience" to "experience and capability of the resource engineers"	Updated.
4.3.2 last sentence	Remove "generated"	Removed.
4.3.3	"engineers experience" to "experience and capability of the resource engineers"	Updated.
4.3.9 2nd sentence	Change "sine" to "since"	Updated.
Figure 4.3-5 Table 4.3-8	FM.5.2, severity shown as 5 but listed as 2, RPN calculated based on S=5	Updated to 2.
4.3.12	Detection for calculation errors should be higher, as it is very difficult to detect errors. Recommend at least 3.	Updated to 3.
Figure 4.3-11	Occurrence and detection should be at least 1 notch higher, based on my experience.	Occurrence and detection updated to 2 and 3, respectively.
4.3.20 2nd sentence	"reminder" to "remainder"	Updated.
4.3.20	First you say detection is 3, then detection is 7. I see where the different FM16's have 3 and 7 in the table, it just isn't clear in the write up. Maybe need to just point to the table for a description.	Added explanation.

Table 60. Part III SME #2 Comments and Resolutions

SME: #3

SME Title: Project Manager

Description of SME Experience:
Project manager for nuclear plant design modifications with more than 15 years of technical engineering experience.

Scope: *Review Part III of the case study and provide comments and/or recommendations on how to improve the content based on your experience with design engineering projects.*

Section/Table/Figure	Comment/Recommendation	Resolution
Section 4.3	Editorial comments. Markup provided.	Updated.
4.3.17	Define SAR.	SAR has been defined.
All 4.3.x	Remove sentence “The engineers in this case study are experienced…” and “Therefore an occurrence…” These sentences are repetitive.	Removed sentences from individual section. Added overall statement to Section 4.3.4.

Table 61. Part III SME #3 Comments and Resolutions

VITA

Pamela M. Torres-Jiménez
Department of Engineering Management and Systems Engineering
Old Dominion University, Norfolk, VA 23529

EDUCATION

D.Eng., Engineering Management and Systems Engineering, Old Dominion University, 2018, Norfolk, VA

M.S., Mechanical and Nuclear Engineering, Virginia Commonwealth University, 2010, Richmond, VA

B.S., Mechanical Engineering, University of Puerto Rico, 2006, Mayagüez, PR

LICENSES AND CERTIFICATIONS

Professional Engineer (PE) – Virginia (License Number: 0402048815), North Carolina (License Number: 039445), South Carolina (License Number: 30095)

PROFESSIONAL EXPERIENCE

May 2012 – Present, Principal Mechanical Engineer/Senior Mechanical Engineer, Westinghouse Electric Company, Charlotte, NC/Rock Hill, SC

January 2007 – May 2012, Mechanical Design Engineer I/Programs Engineer I/Programs Engineer II/Recruiter, Dominion Generation, Surry Power Station, Surry, VA

MEMBERSHIPS

North American Young Generation in Nuclear (NAYGN) – Westinghouse Rock Hill Chapter President – August 2014 – Present

American Society of Mechanical Engineers (ASME) – Member of the Committee for C&S in Spanish – April 2017 – Present

Golden Key International Honor Society – Old Dominion University – March 2012 – Present

The Honor Society of Phi Kappa Phi – Old Dominion University – April 2017 – Present

CONFERENCE PROCEEDINGS

Literature Review on Knowledge Retention, Engineering Design Projects, and License Renewal in Support of the Subsistence of the U.S. Nuclear Power Industry. International Congress on Advances in Nuclear Power Plants (ICAPP), April 8-11, 2018. Author: Pamela M. Torres-Jiménez