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A Better Understanding of Safety of Engineered Systems

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ABSTRACT: *Given the continued increase in scale and complexity of engineered systems, serious safety and risk management issues arise. There have been several catastrophic accidents, which are typically preceded by a number of seemingly unrelated occurrences that add up and cascade across subsystems. In the light of changing software and user interactions in engineered systems, traditional hazard analysis and risk assessment methodologies offer both benefits and drawbacks. Engineers working in contemporary businesses must be able to comprehend the features and characteristics that come from the interactions of components and subsystems as well as the risk assessment tools/approaches.Therefore, the goal of this paper is to increase awareness of the considerations for engineered systems and the risk assessment tools available for safety engineered systems. Specifically, this work focuses on the emergent properties of engineered systems, the various project phases, the available tools, their strengths and limitations and the codes/standards. A case study of the design and construction of a flash gas compression system is presented*

KEYWORDS: Engineered systems, risk assessment tools

INTRODUCTION

The safety evaluation of these systems has become even more crucial in recent yearsas a result of technical developments and a rising demand for highly reliable engineered systems. There have been numerous high-profile, expensive, and occasionally tragic accidents, frequently preceded by a number of seemingly unrelated, but interconnected, incidents. The Deep Water Horizon disaster's incalculable economic, environmental, and human costs (Summerhayes, 2011), therecent grounding of the Boeing 787 line, which is estimated to have cost $5 billion,and the accident involving the space shuttle Columbia (McIntire et al., 2016) are allexamples of the unacceptably high cost of addressing complex failures and safety too late. Unexpected or unforeseen interactions between system components lead tosystem accidents. For instance, the failure of the Mars Polar Lander came as a resultof the designers' failure to account for a specific interaction between the software controller of the thruster and the mechanical leg deployment. The controller misinterpreted a false signal that the lander had touched down on Mars when the legs deployed. While the lander was still 50 feet above the ground, the controller turned off the thrusters, allowing the spacecraft to crash into the earth. Such risks won't be taken into account by methods that solely take failure events into account.Traditional methods for hazard analysis and risk assessment offer advantages and disadvantages, particularly when applied to engineered systems with changing software interactions. Some of the tools assume that accidents are the result of component failure, which ignores the increasingly frequent accidents brought on bysystem and component interactions, such as foam hitting the Orbiter RCC panels orsoftware mistaking the spacecraft for having landed and cutting off the descent engines before they should have. Organizations operating such designed systems frequently face daunting hurdles when developing systems that are softwareintensive, necessitate complicated human decision-making and human-automation interaction, as well as distributed decision-making. An awareness of the risk assessment methodologies is a necessity for engineers working in contemporary organizations, given the evolution and issues in the safetyof engineered systems.

Concept of Engineered System

In order to design a safe engineered system, it is imperative to first define the conceptof engineered systems. *An* **engineered system** *"is a system designed or adapted to interact with an anticipated operational environment to achieve one or moreintended purposes while complying with applicable constraints". It could also beenseen as "a combination of components that work in synergy to collectively performa useful function"* (Edwards, 2009). It is a collection of different systems that interact with one another to achieve a common goal. The likelihood of a negative interaction increases with the number of systems. The entire system completes tasksand produces outcomes that are not possible for any one component to complete alone. More specifically, the behaviors that are emergent characteristics of the entiresystem and not just the behavior of any one particular system component characterize the executed functions.

Usually, numerous distinct engineering disciplines as well as various systems and component kinds are involved when designing and carrying out major engineering facilities and/or operations. As an illustration, in an oil and gas compression project,a variety of systems and components, such as electrical systems, compressors, gas turbines, vibration sensors, structural components, drainage systems, etc., are combined to create a new joint functioning. Each of the parts was created in accordance with rules and/or codes that did not specifically anticipate its use in a compression effort. In this sense, an engineered system can be thought of as an integration of common parts into a particular, frequently distinctive setting. By choosing components that are individually trustworthy enough and assembling themin a way that ensures a sufficient level of safe and reliable joint functionality, risks can be managed.

Emergent Properties of Engineered Systems

Engineered systems have three emergent properties: normal emergence, weak emergence and strong emergence (Mehrpouyan et al., 2016).

Normal emergence is a system characteristic that happens when various parts or subsystems cooperate to carry out an essential task. Therefore, weak and strong emergence are viewed as undesired and even disastrous varieties of emergence, butnormal emergence is a desired system activity. An excellent example of a typical emergence is the air traffic control system. The Flight Management System (FMS),the Instrument Landing System (ILS), and the air traffic controller are each given aspecific and established role in this system. The expected emergent property of the planned interaction of the separate elements and components is the function of a designed system with normal emergence.

The definition of weak emergence, on the other hand, is an emergence that might bepredicted and avoided provided all physical laws were taken into account and thorough simulation and verification were carried out. The Mars Polar Lander is oneinstance of weak emergence (N. Leveson et al., 2012).

In this accident, software mistook the Lander strut vibration for a landing signal. Software switched down bothengines as a result, and the lander collided with the planet. The catastrophic failure might not have occurred if the system, including the software, the physical system, and their interactions, had been thoroughly validated using thorough simulation of the strut's vibration.

Last but not least, one of the most challenging types of emergence to recognize is strong emergence. By definition, this kind of emergence is caused by entirely random forces, and it frequently is human factor related. Strong emergence can be seen in the description of the Nagoya incident. In one instance, the pilot accidentallygave the wrong command to the flight control system, which led to the loss of boththe pilot's and the passengers' lives.

Project Lifecycle of Engineered Systems

There are 12 major phases involved in engineered systems project, typical of any project (Johnstone & Curfew, 2011)

a) Feasibility study phase
b) Concept Development/Concept Design phase
c) Pre-Front End Engineering Design (Pre-FEED)
d) Front End Engineering Design (FEED)
e) Detailed Design
f) Procurement
g) Onsite/Offsite fabrication
h) Site construction, commissioning and start-up
i) Operations
j) Abandonment

Feasibility study phase

The goal of a feasibility study or analysis is to evaluate the viability of several feasible concepts or "ideas" for the project or opportunity's functionality. A feasibility study makes that a project is economically, technically, and legally feasible. It informs the owner or client if a project is worthwhile. A project might not always be advantageous. Numerous factors, like the need for excessive resources, poor market demand, the lack of neighboring resources, etc., can affect this judgment.

Concept Development / Conceptual Design

The multiphase process that goes into developing a new project or product begins with concept development. The proposed product is described using drawings or models. In this phase, a collection of interconnected ideas and concepts are chosen.In the field of engineering, conceptual design is a collection of disciplines that helpsto determine the best design for industrial processes or products under ideal operating conditions. Process flow diagrams, functional requirements, process design, the HMB (Heat and Material Balance), and other key deliverables are vital at this point.

Pre-FEED (Preliminary Front End Engineering Design)

Pre-FEED establishes the parameters that will constrain and define the concept as well as the design development framework. The following steps can streamline thisprocess: creating a design basis that outlines the project's operational characteristics;determining the exercise's technical and financial viability; evaluating the allocationof additional funds for moving forward with engineering and design; and creating project boundaries to address rules and regulations, national and local laws, governance, and content issues. Key deliverables at this stage include: material selection and specification, plant capacity requirements, product specifications, critical plant operating parameters, available utility specifications, process regulatory requirements, all other operating goals and constraints desired by the plant owners/operators/engineers, definition and sizing of main equipment resultingin in-process specifications, preliminary plot plan.

FEED (Front End Engineering Design

After the conceptual design and feasibility study are finished, the front end engineering design, or FEED, is carried out. At this point, numerous investigations are conducted to identify technological problems and provide educated guesses about investment costs. FEED Package is the stage's end result. Normally, bids for the EPC Contract are based on the FEED package. The FEED Package must take the client's goals and project-specific requirements into account. Significant alterations are avoided throughout the EPC Phase. Final plot design, P & IDs (Pipingand Instrumentation Diagrams), MDSs (Mechanical Data Sheets), Line List, Instrument and Valve Data-sheets, and General Arrangements are a few examples of important deliverables. Main equipment and main pipework drawings, safety studies reports (such as HAZOP), project execution plans, health and safety action plans, and operational philosophies are also part of the deliverables at this stage

Detailed Engineering

A study that creates every component of project development is called detailed engineering. Before project building begins, there are numerous studies that are partof the detailed engineering. Detail engineering involves extracting all pertinent data from the basic engineering drawings/FEED, performing calculations to produce precise drawings in detail for production, fabrication, and erection items, anddocumenting the specifics of the entire project, including a precise bill of quantitiesand equipment specifications. 3D-Modelling. Key deliverables include: EquipmentList, Process data-sheet, update of P& ID with vendor data, Valve List, Control valvedata-sheets, Relief valve data-sheets. Detailed piping drawings, including isometrics and stress calculations, Bill of Quantity (BOQ). MTO (MaterialTake-off), Start-up procedures, Operating and Commissioning manuals.

Procurement Phase

procurement team. It is essential to purchase the required goods or services from the top suppliers or vendors in order to get the highest value and performance. These products include supplies, tools, machinery, instruments, and raw materials.

Onsite and Offsite Fabrication

Offsite fabrication is the process of creating and assembling parts or systems offsite,such as in a workshop. By permitting the assembly of units that would otherwise beunable to be manufactured on-site due to cost, tooling, the availability of resources,or space limitations, off-site fabrication offers a cost-benefit. Fabrication done on- site is fabrication done at the project location. After the off-site fabrication, it is stillnecessary to perform fabrication work on the job site in order to link the various systems, pipes, and other pieces of equipment for installation.

Onsite Construction, Commissioning and Start-up phase

Construction is the process of assembling various components and products. To produce a structure, piece of equipment, building, etc., it should adhere to a thoroughdesign plan and installation drawing. The land must be leveled, cleared, and excavated. It also involves various tasks related to the plant's framework, construction, and other elements, such as the foundations and plinths for the equipment. Erection and installation follow this. Cleaning and preparing the area where a new piece of machinery or equipment will be installed is known as erection.It entails setting up tools, equipment, or other components for the purpose of installation. This is the final step in the mechanical process. Installation is the process of joining the various components of the system together mechanically or by welding. Making connections is a necessary step in the formation of a singlesystem. The next is mechanical completion and it has to do with installation of the equipment and piping system. The essence is to ensure that everything is installed as per the drawing.

After the system is mechanically complete, pre-commissioning processes begin. Cleaning, flushing, drying, leak testing, hydro-testing, and other pre-commissioningprocedures are performed on the equipment, piping system, and other operational systems. Pre-commissioning tasks are occasionally incorporated into mechanical completion, although again, this relies on the terms of the contract or the demands of the project. In order to ensure that a facility or a process has been built, purchased, fabricated, installed, tested, and made ready for usage or production according to theclient's blueprint, design drawings, and specifications, commissioning is a verification procedure. It is the project's second to last stage. Note: If there were noerrors discovered in the system during commissioning, the referred drawing becamea "as-built drawing."

As-built drawing is the final drawing sheet of the plant and used for future modification, maintenance, and review purposes. After successful completion of thetesting of the processing system or the plant, the system is ready to start production.

Risk Assessment Techniques for Engineered Systems

Over time, a variety of methods for risk analysis have been developed for the designof engineered systems. Reliability-based techniques and hazard-based techniques are two distinct groups of methods that are typically used to address safety analysisof system design (Mehrpouyan et al., 2016), as shown in Figure 1 below. The foundation of reliability-based techniques is the identification of faults and theirpropensity to develop during the course of the system life cycle. The hazard-based approach is focused on undesirable system states and concentrates on figuring out how likely it is for certain routes to exist. As a result, reliability-based approaches are fault-centric, whereas hazard-based strategies are system state-centric.

Reliability-based techniques

This category of reliability analysis techniques is based on the conceptual models offailure scenarios inside a design and their symbolic logic. The objective is to evaluatethe likelihood that the system design will fail. The Reliability Block Diagram (RBD),which separates the system into elements based on the functional model of the system design and assigns a reliability factor to each block, is one of these techniques. The components of a parallel, series, or hybrid of parallel and series arethen represented in a block diagram. Each block represents a system function or event, and each component's failure mode is believed to be independent of the others.The reliability factor is subjective and challenging to validate because it may or maynot be available for all the system design components and because it should only beprovided by a specialist.

Failure Mode and Effect Analysis (FMEA), a bottom-up approach to reliability analysis, looks into component failure modes and how they affect the rest of the system. In actual use, a top-down analysis is used to support this technique and verifythe analytical resolution. The single point of failure and its impact on the rest of thesystem are thoroughly analyzed using FMEA. The analysis's findings are utilized toimprove design efficiency, add mitigation, and boost reliability. FMEA is, nevertheless, exceedingly resource-intensive, especially when applied at the component level in complex systems. Additionally, instances of numerous faults andsimultaneous failures are not assessed. Expert analysis is key in the completeness and correctness of the analysis

Another reliability analysis method represents the system design for study using functional modeling. One such technique is the Function Failure Design Method (FFDM). By connecting system functionality to failure modes and product function to system design principles, FFDM can be used not only in the early stages of system design but also throughout the whole design process. The Risk in Early Design (RED) method is based on the FFDM technique, which formulates the likelihood of each functional failure and the consequences that go along with it. The fact that RED cannot help designers effectively detect errors during the design phase is a significant disadvantage. Other syntaxes cannot be scaled by the knowledge-based repository utilized by RED to deliver relative failure information. Other research initiatives have raised awareness of the significance of failure cascades in reliability analysis as a means of overcoming these restrictions. The Function-Failure Identification and Propagation (FFIP) approach combines failure identification analysis with model-based reasoning to detect functional failure in the early stages of system design.

Hazard-based techniques

Systems that shift from a hazardous state to a failure state depending on a set of initiating processes are the subject of hazard-based approaches. Therefore, the goal of hazard-based methodologies is to identify potential dangers as well as the mechanisms and logical progressions of events that, in the presence of those hazards, can cause the system to fail.

Fault Tree Analysis (FTA) is one method, which analyzes the failure propagation path from the initial point to the vulnerable components and rates the seriousness of each failure scenario. One advantage of employing FTA is its capacity to evaluate the likelihood of concurrent failure in complex systems. On the other side, it can become computationally expensive to evaluate complex huge systems probabilistically. In addition, the accurate probabilistic evaluation necessitates a substantial investment of resources.

Event Tree Analysis (ETA) is a different strategy from FTA analysis in that it considers both success and failure occurrences. This method models all possible occurrences, including desired emerging behaviors, defective operations, and normal system operations. However, estimation and consensus on the chance of non- comparative success or failure are challenging.

Another method for analyzing failure risk is called probabilistic risk assessment (PRA), which blends many fault/event modeling techniques, including fault trees and event sequence diagrams, into a probabilistic analysis to help with decision- making.

Hazard and Operability Studies (HAZOP) which is based on modeling the interaction flow between components and recognizing a hazard if components vary from the intended operation of designs, is another method for safety analysis. The identification of such discrepancies is made easier with the use of a set of guidewords. However, HAZOP is unable to create repeatable hazard analyses of the same accident when considering safety analysis based on interactions between components and their intended surroundings. This weakness results from the interactions between several subsystems and their operational environment, which are very dynamic and unpredictable. Additionally, the deviations might be distinguished in many ways based on the knowledge and abilities of the safety engineers. Recent advances in HAZOP beyond the Traditional HAZOP include Computer-HAZOP (C-HAZOP) (Willis et al., 1994) and Procedural HAZOP (P- HAZOP) (Willis et al., 1994).

Systems-Theoretic Accident Modeling and Processes (STAMP), a developing technique, is based on the idea that accidents are the outcome of a number of causative elements that happen unexpectedly in a particular time and place (N. G. Leveson & Dulac, 2005). As a result, rather than being seen as a static entity, the system under study is seen as a dynamic process that is always changing to fulfill itsobjectives and responding to changes in the internal and external environment. Theuse of STAMP models as the foundation for hazard analysis of a complex system has numerous advantages. However, the STAMP approach has two major flaws: the implementation of the constraint fault taxonomy lacks methodological guidelines, and building control models in a large system is challenging.

A specialist is needed to identify the risk based on their experience, regardless of the risk assessment techniques, various approaches/methods, characteristics, advantages, and disadvantages that may apply to each. Therefore, the person (or team) in charge of risk analysis needs to have a thorough understanding of past andpotential failures.

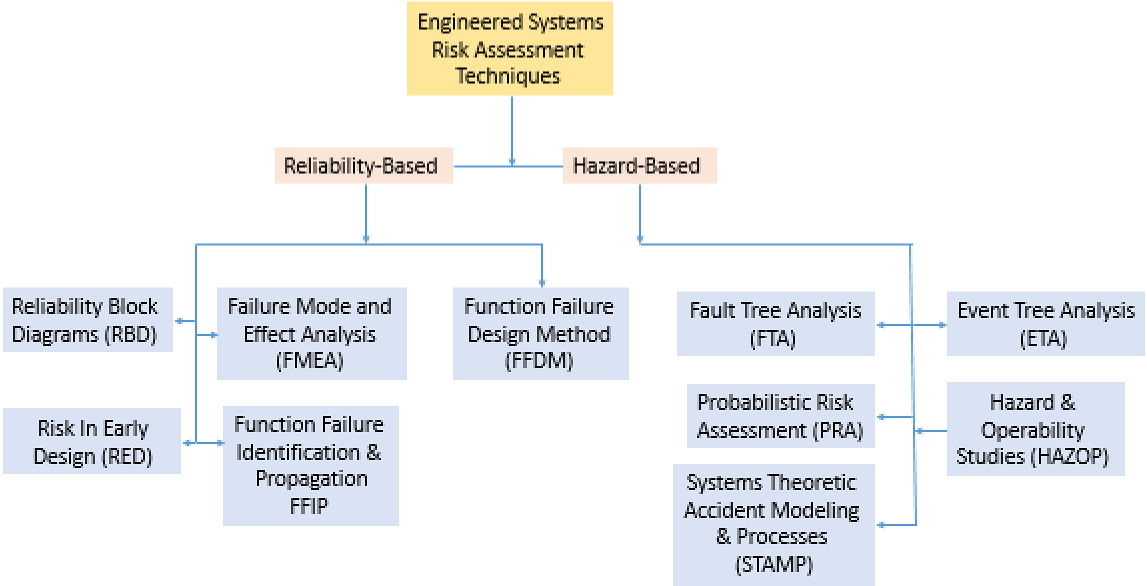

Figure 1: Categories of Risk Assessment Techniques for Engineered Systems

Safety of Engineered Systems – Standards

Several process standards exist that describe “engineered systems” and are mostlyin the so-called Systems Engineering processes (Guey-Shin Chang, Horng-Linn Perng, 2008).

a) MIL-STD-499 Series
b) ANSI/EIA 632
c) IEEE 1220
d) ISO/IEC 15288

MIL-STD 499 Series

The early development of engineered systems (Systems Engineering) and the standardization of its processes were greatly influenced by these military standards.The first standard in the series, MIL-STD-499, was released by the US Air Force in 1969. It was later revised and reissued as MIL-STD-499A in 1974 with the new title "Engineering Management." The main goal was to help government employees and contractors define the Systems Engineering effort to support defense initiatives. As the draft of MIL-STD-499B ("Systems Engineering"),

MIL-STD 499A was modified and expanded. It was never, nonetheless, formally published. MIL-STD-499B was discontinued as part of the 1990s Acquisition Reform movement, which canceled or replaced practically all US Directorate of Defense (DoD)-exclusive military specifications. In December 1994, a "commercialized" version of the May 1994 edition of MILSTD-499B known as theinterim industry standard (EIA/IS-632) was released.

ANSI/EIA 632

Similar to MIL-STD-499B, this standard was first released in 1994 as an interim standard. It was updated and republished as "Processes for Engineering a System"in January 1999. The main goal is to offer a developer a comprehensive collection of essential methods to help with the engineering or re-engineering of a system. It gives 33 requirements necessary to complete the 13 procedures that are directly related to the technical features of engineering systems.

IEEE 1220

The systems engineering methods outlined in EIA 632 are further described in this standard, "Application and Management of the Systems Engineering." The IEEE 1220 document was first released in 1995, however it was later updated and published as a complete standard in 1998. A standard for managing a system from conception through development, use, and disposal is the main goal.

ISO/IEC 15288: 2002

Despite being decommissioned, this standard, "Systems Engineering—System Life Cycle Processes," still applies to the entire life cycle of systems, including their conception, development, manufacture, utilization, support, retirement, and procurement and supply. The procedures outlined in ISO/IEC 15288 establish "a standard framework from describing the lifetime of systems generated by people" and encompass the complete spectrum of acquisition, program management, and technical development.

ISO/IEC 15288:2008

The "Systems Engineering—System Life Cycle Processes" standard, which replaced ISO 15288:2002 in January 2008, establishes a common framework for the description of the life cycle of man-made systems. It describes a set of processes and associated terminology for the full life cycle, which includes conception, development, production, utilization, support, and retirement. It also supports the definition, control assessment, and improvement of these processes. Aligning Systems Engineering standards and software development standards
ISO/IEC 12207:2008 is one of its development's objectives (SystemsEngineering—Software Life Cycle Processes).

Other Specific International Codes & Standards

1) ISO 17776-2002: Guidelines on tools and techniques for hazardidentification and risk assessment, 2002
2) BS: IEC61882:2016: Hazard and operability studies (HAZOP studies) -Application Guide
3) CCPS – AIChE: HAZOP Studies and other PHA Techniques for ProcessSafety and Risk Management
4) IEC 61511: Functional safety - Safety instrumented systems for the processindustry sector (2016 edition)

Nigerian National Standards & Regulations

a) HAZOP forms part of the overall project risk management process which isrequired to be submitted to DPR, as part of the facility Safety (Case) Report

b) Guidelines for Compliance with the Technical Safety Control (TSC) Requirements, June 2000

c) Procedure Guide for the Design and Construction of Oil and Gas Surface Production Facilities in Nigeria, March 2001

A Case Study: Flash Gas Compression System in Niger-Delta

Recovery of associated gas was initiated as part of the flares down program in Niger-Delta. Several options of recovery of the gas were evaluated and the optionof using gas engine-driven centrifugal compression system was selected in a 1- stage compression process.

The FEED exercise - process simulations, process design, functional and technicalspecifications, etc. was executed in-house. A FEED HAZOP was carried out to ensure that the balance of plant design was safe. A preliminary Safety Integrity Level (SIL) classification exercise was carried out on the balance of plant design, after update of the P & IDs with the HAZOP recommendations. Functional specifications, technical specifications and equipment datasheets were prepared aspart of the FEED exercise. Process and Instrumentation Diagrams were issued as “Approved for Design” (AFD) version.

During the Detailed Engineering Design, a “Request for Quotation” (RFQ) was launched for the compression system to packaging vendors and following bid evaluations and clarifications, a purchase order for the compression system was placed on one of the packaging vendors. The packaging vendor designs for the compression system were integrated to the balance of plant design and a HAZOP exercise was conducted on the fully “engineered compression system”, followed by SIL classification of all the safety instrumented systems after update of the P &IDs with HAZOP recommendations. Following this, the P & IDs were issued as

“Approved for Construction” (AFC) version. This was followed by approval of thepackage layout drawings, procurement and assembling of the various equipment packages by the packaging vendor. The packaging was done in lien with the Company Packaged Equipment standard, adapted from ISO/IEC 15288 codes/standards

On completion of the packaging, Factory Acceptance Tests (FAT) were conductedat the vendor works before the packages were prepared for shipping. The gas- turbine and compressor were skidded together while the suction scrubber and fin- fan coolers /motors were assembled as off-skid equipment, forming part of the engineered system.

On site, the equipment were installed on the prepared foundations and off-site fabricated spool pieces were used for equipment interconnections. Pre- commissioning tests were carried out, followed by commissioning and start-up.

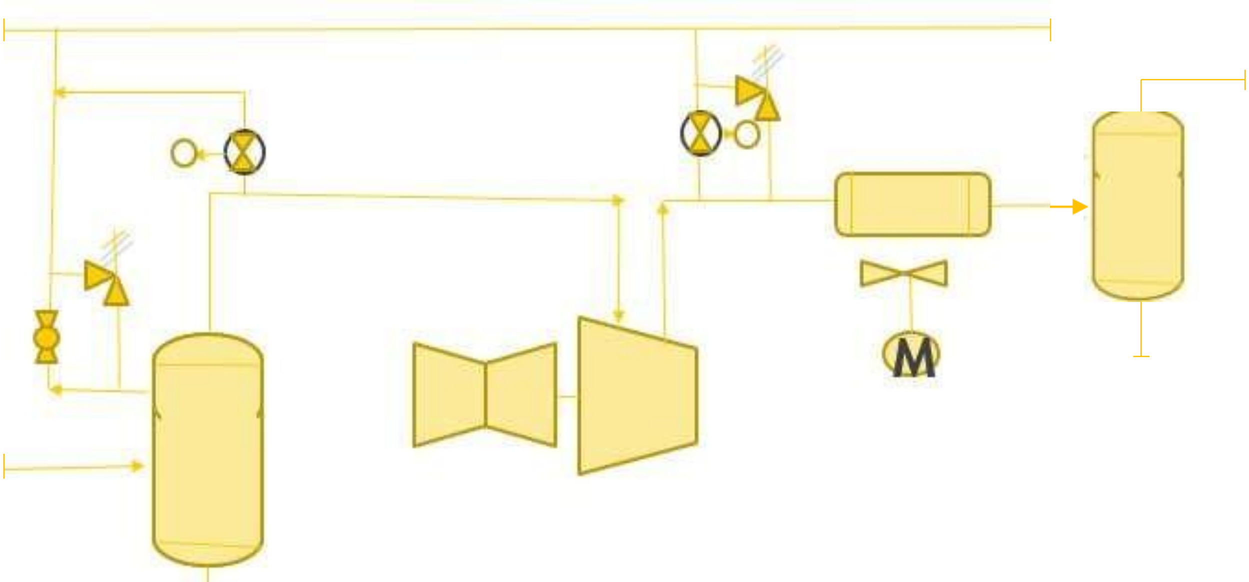

Figure 2: Process Schematic of Flash Gas Compression System

CONCLUSIONS

Accidents and injuries in engineered systems can be prevented if the systems are designed properly using the applicable risk assessment tools for the various stagesof the engineered system project development. Recommended practices, codes, and standards for building safe engineered systems exist and have continued to evolve over the years, following lessons learnt from major accidents. Engineers and operations personnel need to take the time to acquaint themselves with these recommended practices, codes, and standards and become comfortable in using them, to ensure that engineered systems are designed, built and operated without incidents/accidents do not occur.

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