A REVIEW OF SAFETY BY DESIGN PROCESSES FOR THE ENGINEERING OF GEOTHERMAL FACILITIES IN NEW ZEALAND

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ABSTRACT

Geothermal surface facilities, such as steam gathering systems and geothermal power plants, are exposed to a number of unique hazards that present risk to the safety of people and to the environment. An increased level of construction hazard may be present, particularly for the fluid gathering system, which may be spread out over a wide area of often challenging terrain.

In a general sense 'safety by design' is a concept that encourages product designers to 'design out' health and safety risks during design development. This concept is not unique to geothermal design, and covers a range of industry sectors.

An engineering design must consider a variety of sometimes competing criteria, including safety, operational performance, usability, environmental impact, capital cost, operational cost, constructability, redundancy, and future proofing. Project stakeholders will have different views of the important criteria. A good design will need to achieve an appropriate balance of factors. Considering safety by design processes in the engineering of geothermal facilities ensures that safety thinking is considered early and in parallel with other design criteria prior to construction.

A safety by design framework tailored for the engineering of geothermal facilities is presented. Specific processes within this framework, including hazard identification (HAZID) and hazard and operability study (HAZOP) are discussed. The application of this framework is illustrated with design features from specific geothermal case studies.

In New Zealand, the government through the Ministry of Business, Innovation, and Employment is currently seeking feedback on the draft provisions of the proposed Health and Safety Reform Bill. The Bill is part of the Working Safer reform package which will see the Health and Safety at Work Act replace the Health and Safety in Employment Act. The roles and responsibilities of engineers and designers operating under these proposed regulations are discussed in this paper.

1. INTRODUCTION

1.1 Geothermal Hazards

Geothermal piping systems and equipment use hot pressurized geothermal fluid for generating electricity or for direct heat applications. The geothermal fluid can include significant amounts of non-condensable gases (NCG), predominantly hydrogen sulfide (H_2S) and carbon dioxide (CO_2). These gases are asphyxiants and above certain concentrations are highly toxic, and indeed potentially fatal. In addition, geothermal brine contain other impurities, including silica and boron, which can be both hazardous to people and the surface environment. Geothermal fluid, or the NCGs, may need to be discharged to the environment under certain circumstances and these situations need to be carefully considered and allowed for in the design.

In volcanic environments in particular, an elevated construction hazard may be present. This is particularly so for the gathering system which may be spread out over a large area of often challenging terrain. Additionally topographical geo-hazards such as lahar flow paths, areas of steaming ground, and areas with hydrothermal eruption risk should need to be considered.

1.2 Power Generation Capital Plant Hazards

In the case of geothermal power generation a number of energy conversion technologies, or power cycles, can be utilized to convert the geothermal fluid energy into electricity. Common options for power plants are flash condensing steam Rankine Cycles, Organic Rankine Cycle (ORC), or hybrid configurations. The choice of power cycle is based on the nature of the geothermal resource, along with commercial, environmental and cultural considerations. Caustic soda, biocide treatment agents, acid, hydrocarbons, or refrigerants may be required for some cycles.

More generic (non-geothermal) hazards for generating plant include high and low voltage electrical systems, rotating equipment (e.g. pumps), high fluid temperatures and pressures, elevated working areas and elevated noise levels.

For large projects a construction work force can include hundreds of people from different organisations on site during periods of peak activity. This increases the potential for exposure to hazards and there a number of mechanisms that can be employed to foster an appropriate safety culture (Ware and Hochwimmer, 2000) during this phase of a project. These include contractual requirements, training, inspections and audits, and mobilization meetings. Eliminating exposure to a hazard through the design process is desirable as it reduces the overall risk during the construction of the facility.

Hazards can be to people, assets, environment, or to the local community. Safety hazards (i.e. to people) tend to receive the most attention but sound engineering design needs to consider the wider impact of hazards.

1.3 Facility Lifecycle

Generally hazards are most readily apparent during the construction and operation phases of the facility. It is easy for decommissioning and eventual demolition to be overlooked as these are not 'front of mind' at the outset of a project. It is helpful therefore to consider the lifecycle of equipment or systems as having a number of discrete phases:

- Conceptual Design
- Developed Design
- Detailed Design

- Procurement
- Construction
- Commissioning
- Operation (including Maintenance)
- Decommissioning
- Demolition

The ability to influence the inherent safety of a piece of equipment decreases through its lifecycle. This is illustrated in Figure 1. Considering safety aspects at any early stage of the project (i.e. at conceptual, developed, or detailed design phases) is critical. These decisions will influence the subsequent phases of the project and any later changes may require considerable rework which translates into additional project cost and additional delay. If safety aspects are not addressed, then the outcome will be an increased level of residual risk in the project.

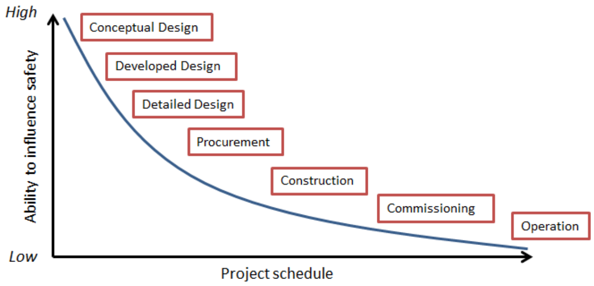

Figure 1: Ability to influence safety on a project by life-cycle (adapted from Szymberski, 1997)

1.4 Safety by Design

Safety by Design (SbD) refers to a suite of design processes aimed at identifying and 'designing out' or mitigating hazards that may arise through the facility lifecycle. A safe design also considers materials and methods of construction and operation, and the appropriate engineering codes of practice and standards.

The overall approach to SbD uses a risk-based assessment, following the general management process from ISO 31000:2009. Safety risks need to be managed through the project. This is done by producing and maintaining a project safety risk register. All identified risks should be adequately addressed through the design process. That is they are either documented and closed out or transferred later into the project lifecycle with acceptance from the assigned party. The process of transferring any residual risk items to subsequent parties (e.g. construction contractor, asset owner/operator) best able to manage them must be considered at the outset of the project.

Safety Engineering is a field in itself, examining safety critical systems across a range of industries and sectors (Leveson, 2011). The material presented in this paper reflects an approach taken for geothermal engineering design, essentially a subset of safety engineering which has been found to be scalable, pragmatic, and provides for design traceability.

2. A SAFETY BY DESIGN FRAMEWORK

2.1 Overview

SbD procedures can challenge assumptions (or blindspots) in the mind of the designer about how a facility might be constructed or used in operation, including misuse in operation.

A geothermal design must consider many different criteria including safety, operational performance, usability, environmental impact, capital cost, operational cost, constructability, redundancy, and future proofing. Project stakeholders will have different, and sometimes competing, views of which criteria are important and a good design will need to achieve an appropriate balance of these factors.

SbD is therefore a multidisciplinary group activity, heavily reliant upon the experience of others (e.g. designers, constructors, operators, asset owners) to achieve the appropriate balance. These are two main sections of the general SbD framework, as shown in Figure 2. These are Hazard Prevention by Design and Design Risk Management.

Hazard Prevention by Design is a set of design steps that are applied in the formative stages of the design process. They embody the approach that 'prevention is better than cure'. Decisions taken later during the design process to address identified hazards are called Design Risk Management. This process can include formal procedures but they require a relatively mature (detailed) design to achieve maximum benefit. If serious issues are discovered at this later stage, then design rework will probably be required.

The general framework is flexible, but the overarching objective is to progressively identify and address safety issues starting from the earliest practical stage in the project lifecycle. Some elements or processes are engineering discipline dependent and are applied when relevant. The minimum requirements we consider to be necessary include:

- Adherence to local legislation, regulations and relevant professional body requirements
- Adherence to client and/or project specific SbD policy, guideline, or process
- Consideration of full asset life-cycle
- Recording the project SbD outcomes, through a completed safety risk register and safety report compiled at design completion

2.2 Hazard Prevention by Design

2.2.1 SbD Plan

A project SbD plan encapsulates the specific approach to be taken, and provides visibility to all stakeholders on that approach. It is an important document.

The SbD plan considers information and standards specific to both the client and project. Relevant 'lessons learned' from past projects are referenced. The SbD approach for the project needs to be agreed, documented in the plan, and approved prior to the developed design commencing.

The plan may also reference general design criteria for the project which can include guidance on SbD thinking. Some example considerations for geothermal design include:

- Design life, redundancy, future expansion and reliability criteria

- Reference to appropriate regulations for platforms and access
- Design guidelines for access, and ergonomic considerations, for operations and maintenance
- Consideration of logical equipment tagging
- Noise limits
- Lighting requirements
- Equipment isolation practices for all types of energy sources
- Pressure relief philosophy
- Provision of safety lines for safety harnesses on pipe bridges
- Physical separation of pipelines from roads
- Pipe support design, e.g. piled stanchion except in the vicinity of power lines
- Standardisation of designs

Application of design principles such as inclusion of visual affordances (Norman, 2002), mapping, designing for error, applying appropriate user constraints are general and not exclusive to geothermal design but underpin many of these considerations.

2.2.2 Standardized Design Components

The design of geothermal steam gathering systems and power generating facilities provide an opportunity for some standardization of component design, equipment selection, and plant layout (e.g. well pads, separator stations, and steam vent stations, electrical and instrumentation equipment).

Where practicable the use of standardized components provides a range of general benefits in terms of constructability, capital cost, operational familiarity, maintenance and project schedule. The operational familiarity can improve operator safety, reduce risk of operator errors and minimize production losses. As operational experience is obtained standardized designs are refined and improved, encapsulating a large number of lessons learned.

An example of this is standard access platforms that are designed to be fully galvanized prior to erection on site, and this avoids the need for any cold galvanizing after erection. We have observed poor platform construction and maintenance practices in some locations which result in unsafe structures after just a few years operation, due to the harsh environment.

2.2.3 SbD Workshop / HAZID

Relatively early in the project, when the design is still developing, is the best time to make the most significant changes with minimal impact on cost and rework. Sufficient preliminary design information and drawings should be available to review. In our experience the 20% design completion stage is a reasonable guideline for the SbD Workshop / Hazard Identification Study (HAZID) session.

The focus of this workshop is to review the project concept from an overall safe life-cycle perspective, and document safety risks on the safety risk register.

Even with collected experience from a range of participants, thinking ‘outside the box’ is not easy. There are two general approaches taken to assist in this process:

1. Provide a series of new categories to think in, called guidewords, that cover a large array of possible risk causes
2. Undertake a verbal or virtual ‘walk-through’ of the design, covering each of the key design features and their life cycle

Our approach is to combine these in a hybrid approach, i.e. design area then guideword. One guideword approach is the HAZID which considers ‘forms of energy’ (e.g. pressure, gravity, electricity) as sources of hazards. This can be combined with a Hazard Analysis (HAZAN) process which works through consequence and impact to rank hazards.

2.3 Design Risk Management

Design risk management can be considered in two ways: i) appropriate consideration from the designer in the design process; ii) standalone design risk management tools.

2.3.1 Management of Risks during Design

Designers always consider project hazards as part of the design process. This consideration includes reference to open risks on the safety risk register, plus recording of any new project hazards that become apparent. Often this process happens in a collaborative way during multi-disciplinary design co-ordination and review meetings.

A hierarchy of controls is considered in the treatment of each risk - the first, elimination, being the preferred control:

1. Elimination of the hazard, i.e. design or engineer out the hazard. (e.g. move discharge equipment away from traffic areas)
2. Substitute a less hazardous material, process or equipment
3. Redesign equipment or adjust a work process
4. Consider administrative controls, for example adjust the time or condition of risk exposure
5. Personal Protective Equipment (PPE)

If a hazard is not identified and treated in the design phase, then less desirable controls may need to be included later, and retrospectively, in the project lifecycle. This can translate into increased operational costs and unnecessary exposure to hazards. Accordingly effective and timely SbD outcomes can provide life cycle cost savings to a project.

2.3.2 HAZOP/CHAZOP

A Hazard and Operability Study (HAZOP) is a structured risk assessment intended to identify potential deviations from the design intent through the use of guidewords. HAZOP is applied to process and material flows. This study is scheduled when Piping & Instrumentation Drawings (P&IDs) are substantially complete. It was originally developed in the 1960s by ICI Chemical (Kletz, 2006), to identify and evaluate safety hazards in a process plant, and to identify operability problems that, although not hazardous, could compromise the plant's ability to achieve design productivity. A HAZOP concentrates on exploring the possibility and consequences of deviations from normal or acceptable conditions, and in this way forms a “check” of the design.

A Control Systems Hazard and Operability Study (CHAZOP) is similar but is focused on instruments, controls and computer systems. Again this references P&IDs as nearly all geothermal facilities include some level of process control and instrumentation. The process description and electrical single line diagram should be substantially complete prior to this study.

The HAZOP process is conducted in accordance with international standards, IEC 61882-2001: Hazard and Operability Studies (HAZOP Studies) – Application Guide.

2.3.3 Reliability, Accessibility, Maintainability, Buildability, and Operability (RAMBO) Review

Constructability, or “buildability”, reviews are reasonably common place in the engineering design process. Constructability is a test to understand if design is both feasible and safe to construct. It is normally undertaken after the civil/mechanical/structural layout drawings are developed.

A RAMBO review considers a broader scope outside of a traditional constructability review. It is a guided checklist approach using the key guidewords: reliability, accessibility, maintainability, buildability, and operability. It is a particularly useful process in identifying action items to improve the design, primarily around SbD, but often can provide other benefits. In conjunction with topographical information, this is valuable relatively soon after completion of the concept design when the design philosophy can still be efficiently modified if required.

2.3.4 Safety Integrity Level (SIL)

Functional safety describes systems which provide safety to personnel against the risk of plants or processes which may develop a fault which could create a life threatening event. The risk is formally defined as one of ‘misdirected energy’. The safety system must provide controlling action, which will place and/or maintain the process in a safe state. The system to be engineered has a clearly defined safety function. The functional safety system should be designed to operate independently of the normal process control system.

The performance of these systems is now measured in terms of their Safety Integrity Level (SIL). This is a fairly recent (mid 1990s through Instrument Society of America standard ISA S84.01 and subsequent industry neutral standard IEC 61508) concept to provide a simpler measure of the reliability achieved with such a system.

A SIL analysis is not typically undertaken in the geothermal industry, as other design processes provide for an acceptable approach in identifying and treating risks. Some geothermal developers, particularly if they have a background in the Oil & Gas sector, are comfortable with the SIL analysis and design processes and in these cases it can be included in the overall project framework if required. A SIL analysis may be implemented as part of upgrading an existing plant control system.

2.3.5 Facility Layout Review

A formal facility layout review should be conducted reasonably late in the general arrangement development process to address inter-disciplinary issues. It should be stressed that throughout the development of a design, inter-discipline co-ordination is essential, and informal layout review is an ongoing process ahead of this formal review.

2.3.6 Design Completion and Construction Phase

A design submission that is ready for construction should be accompanied with a safety report (which may be a section of an overall design report). This report documents risks that have been identified and addressed through the design process. Importantly it documents any residual hazards to people, assets, the environment, or community that have a risk to subsequent lifecycle phases, i.e. construction onwards.

It is also important that future decision makers are familiar with the safety controls that are incorporated into the facility design. This allows informed decisions about making alterations to the design when such needs arise. Without understanding the underlying safety and risk control strategies intended by designers, downstream decision makers may unwittingly compromise the intended integrity of the original design.

SbD continues during construction. Often a design may require minor changes during construction to deal with unforseen issues. Identification and treatment of any associated risks are documented in site notes or alternatively included as amendments to the project safety report.

2.4 A Flexible Approach

The standard process outlined in section 2.3 is conventionally implemented as a gated, once-through sequence. However, it can also be flexible to the scale and complexity of a project. The nature of many geothermal projects is that they have significant overlap between the drilling, above ground facilities design, procurement and construction phases, which may preclude a simple step-by-step SbD sequence. Fortunately, many of the design elements of the project, such as the designs for wellpads, separator stations and pump stations may be identical or substantially similar.

For instance a HAZOP can be undertaken on representative elements of a design along with the interlinking main piping. The decision on the need for, and scope of, subsequent HAZOP studies can be assessed by considering whether:

1. The new section of plant is sufficiently similar to an already HAZOPed representative section that no further review is warranted. Identified minor differences are documented, with the basis for the decision; or
2. The new section does warrant further study, in which case the scope and extent of the study (which may be a ‘Mini-HAZOP’) can be determined.

This approach provides the opportunity for the design process to proceed in a timely and efficient manner, without unduly compromising the quality of SbD input or requiring excessive, semi-repetitive effort (Figure 2). It does rely on the experience and judgment of those who must make the assessment of when further SbD reviews are warranted.

3. SELECTED CASE STUDIES

The application of the SbD framework is illustrated with design features from two specific geothermal case studies.

3.1 Te Ahi O Maui Geothermal Project

The Te Ahi O Maui Geothermal Project (TAOM) in Kawerau, New Zealand aims to develop the resource beneath the lands of the Kawerau A8D Ahu Whenua Trust. The TAOM power plant will be designed to generate approximately 15-20 MW net of electricity (depending on the power plant configuration), with around 15,000 tonnes of geothermal fluid extracted daily from the geothermal reservoir.

At the time of writing the project is progressing through the resource consenting process. In parallel to that a SbD plan is being implemented and a HAZID study has been undertaken. The HAZID study, undertaken with the project trustees, identified 74 items covering specific areas like “general/project wide”, “all weather access”, “well pads”, “drilling”, “cross country lines”, “plant area” and “transmission system”. The HAZID had a particular SbD outcome focus for both people and the environment. In particular a number of issues were raised early in concept design, particularly relating to equipment layout relative to existing access and infrastructure. The process was found to be very effective as many of the hazards have been eliminated through relatively straightforward design decisions at an early stage.

3.2 Olkaria IV and I Additional Units

The concept design phase of this 280 MW geothermal power project in Kenya commenced in 2010, followed by detailed design starting in 2011. The steamfield procurement & construction contract was tendered in mid-2011. However, drilling and testing of the production and re-injection wells for the project was ongoing through to mid-2013.

A staged design process was implemented to handle the overlap between the drilling, design and construction schedules, which is common to many geothermal projects. As described earlier, thorough SbD processes, including HAZOP and constructability reviews, were applied to the design of the initial standardised elements (wellpads, separator stations, etc). Review of subsequent design elements could then be performed and documented on a “by exceptions” basis, considering the nature of any differences from the already-completed designs. Several “mini-Hazops” were undertaken for non-standard elements of the later design work, such as cross-country brine piping networks and interconnections with the existing Olkaria I and II steamfields.

KenGen’s Olkaria IV and I Additional Units project is largely located within the Hell’s Gate National Park, so many of the roads see tourist traffic as well as the usual operations and maintenance vehicles. The design and layout of the project needed to take this into consideration. To minimize the risk of vehicle impacts, KenGen requested that cross-country pipelines were kept at least 5m back from road edges, or protected by crash barriers in any localized areas where this was not possible.

There are a number of pipe bridges installed for this project. One of these was required to cross a gully alongside which an existing 33 kV overhead line was running. The line was not able to be relocated, but could be de-livened temporarily. A combined safety and constructability review was undertaken for the bridge. This review considered various options for orientation and design of the bridge, including aspects such as:

- ➢ the specific location of the bridge, abutment, pipeline and pipe supports, to allow construction and installation with minimum risk to personnel or the power line
- ➢ the structural frame design (particularly the height), and the position of the pipeline on this frame
- ➢ clearance below the power lines with respect to potential maintenance activities on the bridge
- ➢ the potential for members of the public to climb onto the bridge, despite the fact that it was not intended to provide permanent pedestrian access

The rock mufflers for venting excess steam from the steamfield needed to be sited in the general vicinity of the two power plants. The specific location was selected with due consideration of the potential for gas and steam discharges to impact traffic on public and private roads, overhead transmission lines, operations and maintenance personnel and power plant equipment (most notably the cooling towers). The prevailing wind patterns and topography were reviewed in relation to steam & gas dispersion and noise emissions. The steam vent control valves were located some distance away from the concrete muffler chambers, to help reduce the effect of steam and gas on personnel working on the valves. The entire steam venting area was fenced off to prevent unauthorized access.

4. LEGISLATIVE REQUIREMENTS FOR ENGINEERING DESIGN

4.1 Current Legislation

The roles and responsibilities of individuals to consider SbD vary according to the legislation in place in each specific country. When SbD principles are covered by legislation, then engineering designers must demonstrate they have systematically identified risk in their design process, and that those risks have been reduced as low as reasonably practicable while ensuring the owner is aware of any residual risks.

At this point there appear to be SbD legislative requirements in many jurisdictions around the world including, and not necessarily limited to, Australia, New Zealand, Europe, and the United States of America.

In the New Zealand context the Health and Safety in Employment (HSE) Act 1992 promotes the prevention of harm to all employees, placing obligations on the employers to achieve this through a duty to “take all practicable steps”. Duties extend through regulations to those who control workplaces, or design, manufacture or supply plant or equipment. The Act was further reviewed and amended in 2002.

4.2 Proposed Legislation

For many sectors in New Zealand, including geothermal, improved health and safety regulations are expected following the Royal Commission on the Pike River Coal Mine Tragedy (White, 2013).

A draft Health and Safety Reform Bill is currently under consultation in New Zealand, which includes expansion on the responsibilities of equipment designers and penalties for breaches. It is expected to form the Health and Safety at Work Act coming in to force by 1 April 2015, and will replace the HSE Act 1992. It will also amend the Hazardous Substances and New Organisms Act 1996.

The proposed bill defines a person conducting a business or undertaking (PCBU), and as far as reasonably practicable, this person is to ensure the health and safety of workers and others affected by the work. In this context an engineer or designer has explicit obligations relating to the items that are within their influence.

Assessing the full geothermal facility lifecycle (refer section 1.3) in the design process enables due consideration of stakeholders that may be affected by the design and has good alignment with the PCBU concept.

In addition to the proposed new health and safety regulations Worksafe New Zealand has introduced the High Hazards Unit (HHU). The HHU is tasked with ensuring operators in the high hazard sector are effectively managing health and safety to minimize the risk of a major incident at their sites. The remit of the HHU includes geothermal well drilling and operational activities, with a specific focus on process safety risks (Work Safe New Zealand (2014)).

The HHU has a goal of working with the geothermal industry to develop improved hazard identification and risk assessment processes. The SbD framework and approach presented in this paper is consistent with this goal, with particular focus on early identification and treatment of hazards through hazard prevention by design.

While the SbD approach appears to align well with the proposed new legislation, it is subject to ongoing refinement to meet the new requirements and most importantly continue to be effective in making geothermal facilities safe to construction, operate, maintain and eventually decommission and demolish.

4.3 Obligations of Professional Engineers

Professional engineers are subject to their respective organisation’s code of ethics. These codes are additional responsibilities expected of members consistent with and in addition to regulatory requirements.

Members of the Institute of Professional Engineers New Zealand (IPENZ) have a specific code of ethics, and additionally Chartered Professional Engineers (CPEng) operate under a Code of Ethical Conduct. These sets of rules include clear provisions to consider a risk managed approach to engineering design, and consideration to minimize construction site hazards.

The IPENZ guidelines include recognition to protect life and safeguard people through their engineering activities, with due regard to the following (IPENZ, 2014):

1. Giving priority to the safety and well-being of the community and having regard to this principle in assessing obligations to clients, employers and colleagues
2. Ensuring that reasonable steps are taken to minimise the risk of loss of life, injury or suffering which may result from engineering activities, either directly or indirectly.
3. Drawing the attention of those affected to the level and significance of risk associated with the work
4. Assessing and taking reasonable steps to minimise potential dangers involved in the construction, manufacture and use of outcomes of engineering activities.

5. CONCLUSIONS

A safety by design framework tailored for the engineering of geothermal facilities is presented. All aspects of the facility life-cycle (i.e. construction, operations and maintenance, decommissioning) are considered. The process is robust, inclusive of relevant stakeholders, and meets current regulatory requirements and relevant standards.

A new health and safety reform bill is currently under consultation in New Zealand and expected to come into force in April 2015 as the Health and Safety at Work Act. On-going effort is underway to align this SbD framework for geothermal design to the new requirements.

The approach presented here has been applied in a number of geothermal projects providing significant benefits for the asset owner and the safety of their operators.

Outside the traditional elements of process safety review (HAZOP) which are well defined and understood in industry, the approach provides more definition around other SbD tools and their application to geothermal facility design. The framework provides for an effective approach in understanding and addressing hazards early with consideration for the facility lifecycle.

Design must consider different criteria and drivers including cost. The project location, with respect to local safety culture towards construction and operation, can also be a consideration. Including a defined safety by design framework in the engineering of geothermal facilities enables safety thinking to be considered early and in parallel with other design criteria prior to construction.

Effective SbD outcomes can also provide life cycle cost savings to a project.

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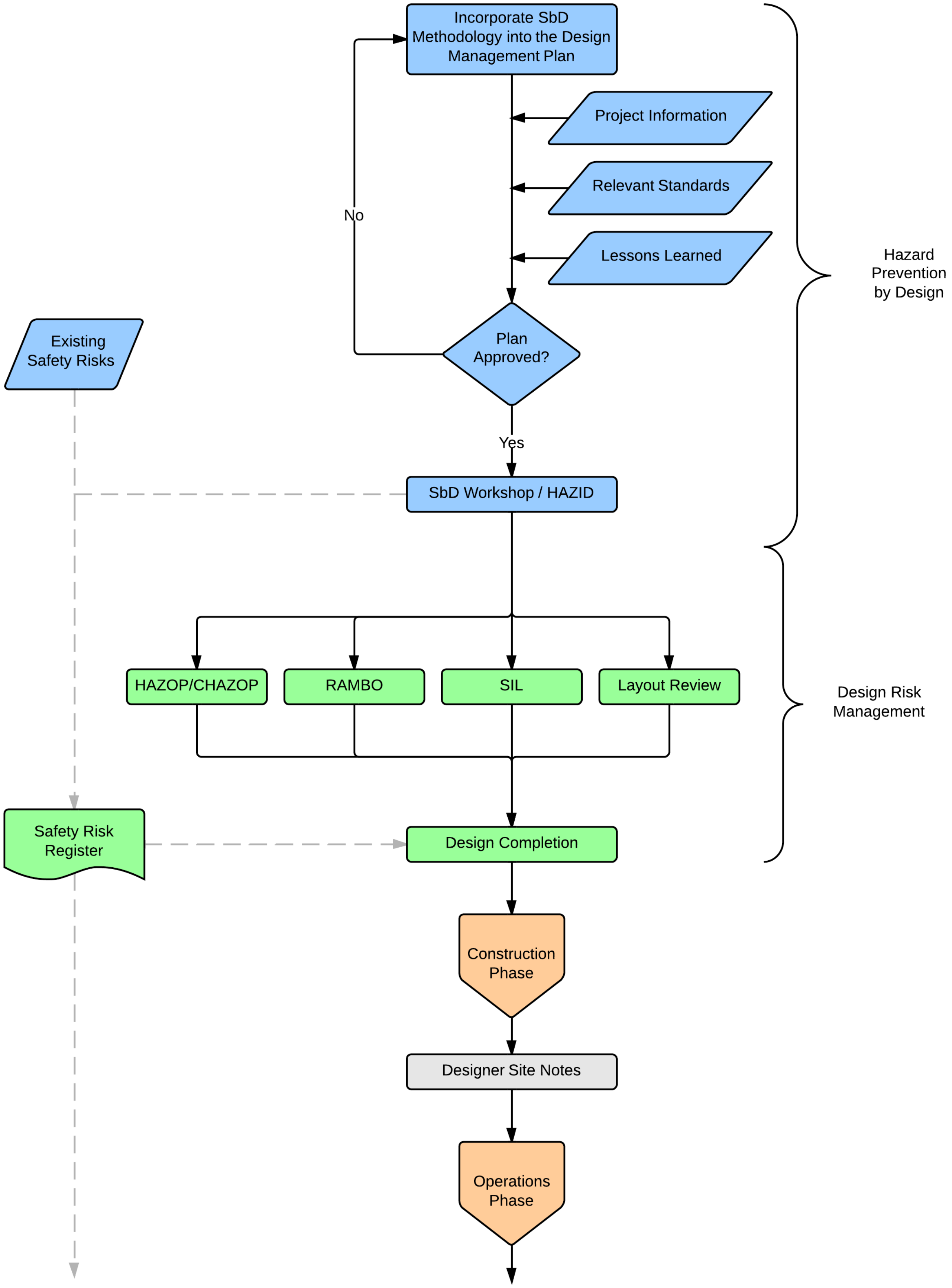

Figure 2: General Safety by Design Flowchart