Process Safety and the Hyperloop

Ian Sutton, Sutton Technical Books, PO Box 2217, Ashland, VA 23005, United States of America

A new type of transportation known as hyperloop is being developed. It is likely that the first commercial applications will occur within the next decade.

Hyperloop technology is profoundly different from that used in the process (chemical and energy) industries; nevertheless, there are similarities when it comes to risk management and the avoidance of major incidents. Both are complex industrial systems, and both have the potential for high consequence events. The lessons that the process industries have learned to do with process safety are relevant to hyperloop. It is suggested that those lessons, expressed in the form of a generic Safety Case, could provide a practical basis for understanding and managing the risks associated with hyperloop.

Keywords: hyperloop, safety case, process safety management, WASH-1400

Introduction

Every so often an industry goes through a fundamental shift in the way it is organized or the manner in which it operates. The chemical industry underwent such a change in the late 1980s following a series of very bad incidents, of which the catastrophe in Bhopal, India in the year 1984 was the worst. It became evident at that time that a fundamental rethink was needed with regard to Process Safety Management (PSM). So, in the late 1980s and early 1990s many PSM regulations and standards were introduced. The industry also created organizations such as the Center for Chemical Process Safety. PSM programs are often organized and implemented through the use of what are known as 'Safety Cases' — the case that management makes to all stakeholders to demonstrate that they have achieved an acceptably low level of risk.

The offshore oil and gas industry went through a similar change following the Piper Alpha disaster in the year 1988. Following that event, and the subsequent publication of the Cullen report (Cullen 1990), companies world-wide invested heavily in Safety Cases and Formal Safety Assessments to help ensure that such an event could not happen again.

Another business which has the potential for high consequence incidents is the nuclear power industry. In the early stages of its growth it was decided to conduct a safety analysis of a generic nuclear power plant. The results of the analysis were published in the Reactor Safety Study (Rasmussen 1975).

Using this nuclear power example, one way in which process safety techniques could be used in the hyperloop business would be to develop a generic Safety Case. Doing so would provide the following benefits.

1. It would provide an overview of the risks associated with hyperloop to all stakeholders, including members of the public.
2. It would show how those risks could be reduced to an acceptable level.
3. It would provide a useful "go-by" that could be used by industry to analyze and control the risk to do with specific projects.
4. It would provide a basis for the development of sensible regulations and standards.

Another industry which is going through a fundamental transformation at present is transportation. New technologies such as drones and autonomous vehicles (EVs) / driverless cars are being introduced and gaining acceptance. And a new type of transportation known as hyperloop is also on the horizon. No hyperloop projects have been commercialized yet, but it is reasonable to expect this technology will be in public use within the next decade.

For all types of transportation safety is a prime consideration. With regard to drones, the public does not want them dropping out of the sky or hitting airplanes. The safety concerns to do with driverless cars are self-evident. So it is with hyperloop — safety will have to be the highest priority.

At first glance, the technology looks to be basically safe. For example, in October 2017 the insurance company Munich Re issued the following statement with regard to the operations of the Hyperloop Transportation Technologies (HTT) company.

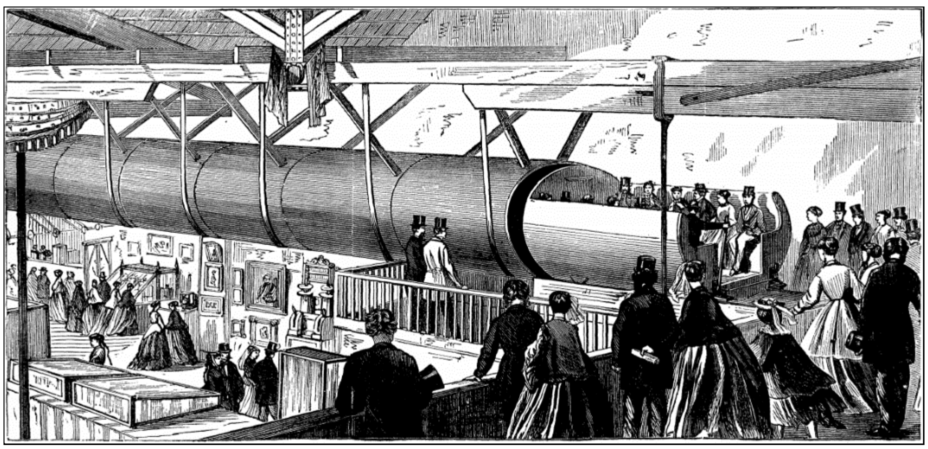
> *Munich Re is of the opinion that the Hyperloop technology developed by HTT is both feasible and insurable in the medium term and that delivering the system demands a model represented by HTT's innovative approach.*

(Munich Re 2017)

Nevertheless, this new technology does pose risks, some of which are of high consequence. Moving people and freight within a narrow tube at very high speeds creates risks that need to be evaluated and controlled. The principles of process safety management can be used to help address these concerns. This is because PSM is fundamentally a *management* topic, and its management insights have a general application, regardless of the industry.

Hyperloop Technology

Many of the ideas that lie behind the concept of hyperloop have been around for many years. As early as the year 1865 a proposal was made for the construction of a system using low pressure tubes in the City of London. Later, in the 1930s, serious consideration was given to the idea of a "Vac-Train" in the United States.



Victorian "Hyperloop"

The word 'hyperloop' was coined by Elon Musk in a white paper entitled *Hyperloop Alpha* that he wrote in the year 2013 (Musk 2013). Evidently, he chose that word to represent a system in which pods in vacuum tubes would circulate in a continuous loop.

It is outside the scope of this paper to provide a detailed description as to how hyperloop works. Moreover, because the technology is still being developed, the basic design will continue to change until the first commercial systems are built. Nevertheless, the following are features of most proposed hyperloop systems.

Not a Train

First, it is important to understand what hyperloop is *not.* It is not a high-speed train. In fact, it is not a train at all. Trains consist of a 'train' of cars (either passenger or freight). Hyperloop modules move independently and are not connected to other modules. In addition, most conventional trains are hauled by a locomotive. A hyperloop system does not have a locomotive; the modules have self-contained method of propulsion.

Not only is hyperloop unlike a train in terms of design, it does not operate in the same manner as a train. For example, conventional passenger trains have scheduled stops along an established route. Passengers board and leave the train at specified times at passenger stations. Hyperloop will more likely provide a point-to-point travel experience. The passenger will call for a module when he or she needs it; it will then go directly to the passenger's destination.

In fact, the transportation model is more like a freeway than a train — independent vehicles will move on their own schedule, entering and exiting the freeway at on/off ramps. The passenger experience will be analogous to that of calling for a taxi, rather than waiting for a train or a bus.

Design Principles

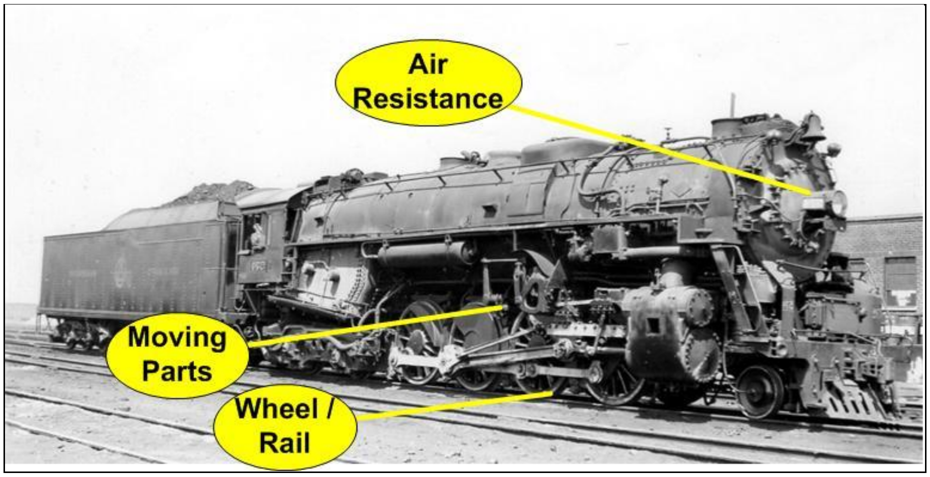
The following are the principles behind the design and operation of most proposed hyperloop systems.

- The modules ride above the floor of the tube using the principles mag(Mag)netic lev(Lev)itation. There are no wheels, except for emergencies, and there is no track.
- Each module is moved forward with linear-electric motion (LEM) motors. An illustration as to how they work is provided in the YouTube video *World's Simplest Train* (Amazing Science 2014).
- Top working speeds are as high as 700 mph (1100 km/h). This speed is comparable to that of a commercial airplane, and is considerably higher than conventional high-speed rail, whose top speeds are in the 200 mph (320 km/h) range.

Friction Losses

The design feature that makes hyperloop so attractive is that the entire system operates with minimal friction. Hence, not only can high speeds be achieved, but energy use is minimized.

Conventional means of transportation have multiple sources of friction which restrict maximum speeds and which reduce fuel efficiency. Consider the old-fashioned steam locomotive shown below.

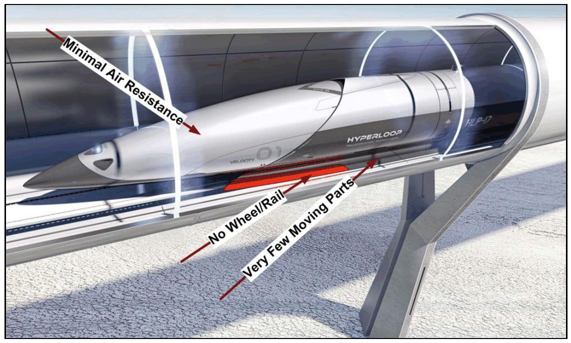


There are three principal sources of friction.

1. *Air Resistance*
   At low speeds air resistance is not a problem. But, since drag increase with the square of velocity, trains that travel at speeds of 100 km/h or greater will generally require streamlining. Even then, air resistance is an important consideration.
2. *Moving Parts*
   A traditional locomotive contains countless internal moving parts, all of which create friction.
3. *Wheel/Rail*
   There is friction at the wheel/rail interface.

Although other, more modern, types of transportation such as high-speed rail are more efficient than an old-fashioned steam engine, they still suffer from the same sources of friction. (Airplanes do not have a ground/wheel contact, but they do have many internal moving parts and experience drag, even at high altitudes).

Hyperloop minimizes these friction losses, as shown in the sketch below.



1. Because the pressure in the tube is very low there is virtually no air resistance;
2. There is no wheel/rail contact because there are neither wheels nor rails; and
3. There are few internal moving parts.

Internet of Transportation

In the minds of many, hyperloop is not merely the next stage in the development of high speed transport. Instead, it has the potential to become the basis of an integrated transport system, analogous to the internet. The following is a quotation from Nick Earle, an executive with the company Virgin Hyperloop One (Earle 2017).

> *I lived through the thick of the data revolution. Think of how not very long ago paper was the primary way we transported data, point to point telephone lines were the way we carried voice, and passing around physical recordings of a picture or film was the way we transported images. Thanks to digitization we can now do all three on a digital packet-switched network that can handle data, voice, and video transportation at very high speeds simultaneously. That has transformed our lives.* ***Transport today is like human communication 20 years ago—separate slow networks incapable of seamless interoperability.*** < *my emphasis*>
>
> *The peak speed of the Hyperloop will be twice that of today's fastest bullet train, but our true time savings will be five to six times greater compared with typical high-speed rail, depending on the route, because every journey is nonstop to your destination, and departures are continuous. What's more, Hyperloop can transport passengers, freight, and cars simultaneously. One of the big lessons of the Internet era was that open interoperability is vital. We're designing the system to accept any autonomous vehicle (AV) that is summoned to pick people up from their home or office, travel long distances, and then complete the last mile of the journey. AVs and drones could do same-day delivery across vast distances without distributed warehousing. Freight could work the same way. One investment collapses separate networks into a single, more efficient network. That creates an explosion of productivity and mass disruption of business models.*

Earle's point is that when the internet was new it was perceived as being too slow. Therefore, the development focus was on increasing speed by moving from modems to high speed connections and then to broadband. Now, given that computer and connection speeds are fast enough for most purposes, the focus is on creating content that can move seamlessly around the internet.

So it is with transportation. The focus right now is on speed — when people talk about hyperloop they almost always focus on the 700 mph speeds that are promised. But, if hyperloop is perceived as being like a physical internet, then it becomes an integrated system that moves goods and people in an entirely different way from what we are used to.

But all of this will only happen if it can be shown that the technology is safe.

Hyperloop Safety

Although the process and energy industries are technically very different from hyperloop, they do have features in common. Hence, it is suggested that the techniques used in Process Safety Management can be used to help ensure that this new technology gets off to a safe start. Some of the features that they share include the following.

High Consequence Events

In the case of the process industries events such as fires, explosions and the release of toxic materials can have catastrophic and life-threatening consequences. In the case of hyperloop probably the event of greatest concern will be the module losing directional stability and crashing into the tube wall at high speed.

Process and Occupational Safety

Broadly speaking, safety programs fall into one of two categories: *process* safety and *occupational* safety. Process safety requires an in-depth understanding as to how a system works, then understanding how low probability/high consequence events can occur, and finally, what can be done to reduce the risk associated with such events.

Occupational safety (sometimes referred to as "hard hat" safety), on the other hand, focuses more on the actions and behaviors of people working in a hazardous environment. It is primarily concerned with higher probability/lower consequence events that impact just individuals or small groups of people.

Each type of safety calls for its own type of response. Occupational safety is usually addressed with detailed rules, regulations and standards. It is also improved through behavior-based safety programs. Process safety, on the other hand, is built around management systems, and often requires the use of sophisticated risk analysis techniques.

In general, a program designed to improve process safety will also create improvements in occupational safety. However, the opposite does not usually apply. Indeed, there have been cases where a company has had an excellent occupational safety record that has created false of security. After the occurrence of a serious incident, the facility manager will almost always say, "I couldn't believe it."

A risk analysis and management program for hyperloop would focus on the principles of process safety.

Freight

Currently most discussion to do with hyperloop technology has focused passenger transportation. But it is likely that there will be an increased interest in moving freight also because, as railroad experience has demonstrated, it is generally much more profitable than moving passengers.

53 ft. High Cube Containers — double-stacked

If hyperloop is used for hauling freight then much of its cargo will be carried in standard 53 ft. 'High Cube' containers, often referred to as inter-modal transportation because the containers can be transferred from ships to rail cars to trucks without the contents being disturbed.

With regard to safety, freight has one big advantage over passenger transportation — if there is a serious incident then there will be no one present, so there will be no fatalities or serious injuries. To paraphrase Trevor Kletz, "If a man's not there, he can't be killed". A focus on freight also removes issues to do with passenger panic, and will make emergency response less critical.

Highly Hazardous Materials

Consideration should also be given to hauling "highly hazardous chemicals" and flammable materials such as crude oil. Currently, in the United States, approximately 60 to 70 freight trains transit the east coast mainline railroad from Florida to New England daily. These trains, some of which exceed two miles in length, haul mostly coal and containers, but approximately 6% of the consist is made up of tank cars containing chemicals and fuels. If consideration is ever given to using hyperloop for these chemicals then the principles of process safety management will certainly have to be applied.

Economic Loss

If there is a serious incident involving hyperloop the economic losses could be very high. Whereas the loss of a single drone or driverless automobile does not have major economic consequences, large incidents in the both the process and hyperloop industries can lead to severe economic loss because both systems are so capital intensive.

Elements of Process Safety Management

In order to understand how the principles of Process Safety Management (PSM) can be applied to hyperloop safety, it is important to consider the core elements of a PSM program.

Management

Process Safety Management (PSM) is fundamentally a *management* program. It provides all employees with the tools that they need to understand and then control high-consequence hazards. Fundamental to this strategy is an understanding that PSM is both non-prescriptive and performance-based.

A non-prescriptive standard is one in which an outside regulator does not provide detailed rules as to what the operating company must do. Instead, the regulator says to the operator, "You know best how to design, operate and maintain this facility. Do what it takes to be safe".

The other side of this coin is that such an approach has to be performance-based. Since the operator is not being measured on compliance with specific rules, he or she must show that the facility is operating at or below the level of "acceptable risk".

CCPS Structure

Because PSM is performance-based, each company will develop standards and management practices that best address its own circumstances. There cannot be a one-size-fits-all program. Nevertheless, many organizations have published guidelines that provide a sensible structure for most companies to follow. For example, the following structure, which was developed by the Center for Chemical Process Safety (CCPS), is both representative and widely used. It consists of 20 management elements.

1. Process Safety Culture
2. Compliance
3. Competence
4. Workforce Involvement
5. Stakeholder Outreach
6. Knowledge Management
7. Hazard Identification and Risk Management
8. Operating Procedures
9. Safe Work Practices
10. Asset Integrity / Reliability
11. Contractor Management
12. Training / Performance
13. Management of Change
14. Operational Readiness
15. Conduct of Operations
16. Emergency Management
17. Incident Investigation
18. Measurement and Metrics
19. Auditing
20. Management Review

These elements link and interact with one another. To take a simple example, we cannot Train an employee in the tasks that he or she is expected to perform (element #12) without first writing Operating Procedures (element #8). But, before we can write the procedures, we need technical information (element #6).

Hazards Analysis

At this stage in the development of hyperloop one of the most important tasks is to conduct preliminary hazards analyses (element #7 of the CCPS list).

To do this, it is first important to understand the nature of risk, as shown in the following equation.

$$Risk_{Hazard} = Consequence^{n} * Predicted\ Frequency$$

where $n > 1$

(The exponent ‘n’ is used to show that risk is fundamentally subjective, high-consequence / low-frequency events are generally considered to be less acceptable than small, higher frequency events.)

The risk analysis process consists of the following steps.

1. Identify the hazards — those events that have the potential for a serious incident.
2. Estimate the consequence of each hazard, considering not just safety, but also environmental and economic impact.
3. Assess the predicted frequency with which the hazard may occur.
4. Develop a risk estimate for each hazard.
5. Reduce the risk associated with those hazards that are considered to be unacceptable. Ideally, this is done by removing the hazard altogether. If this cannot be done, then measures should be taken to reduce the consequences of the event. If that is not sufficient, the predicted frequency should be reduced. (If all of these measures fail to achieve the goal, then safeguards will be needed.)

In the case of hyperloop, hazards to consider are:

- Total loss of electrical power.
- Rupture of the tube leading to a small air leak.
- Rupture of the tube leading to a large air leak.
- Failure of the braking system (there are no wheels or track, so conventional braking is not possible).
- Failure of the emergency landing gear.
- Passenger panic.
- Failure of communications with the control center.
- Loss of directional stability.
- Seismic activity.

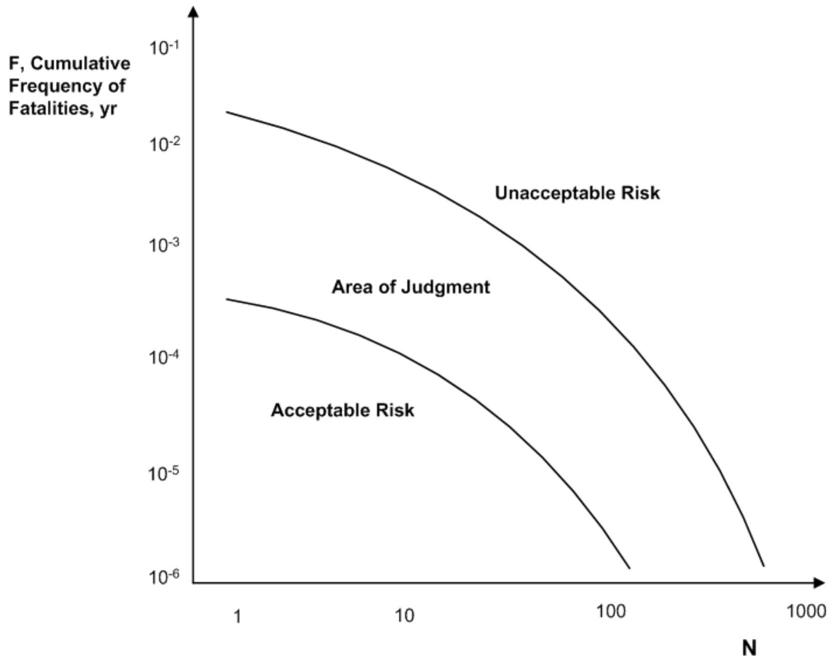
Some consequences associated with these hazards are:

- Module strikes inside wall of tube at high speed, leading to loss of life and extensive damage.
- High pressure in the tube causes the module to move slowly or come to a complete stop, leading to potential passenger panic.
- Module goes around a bend too fast, leading to passenger injury and/or freight damage.
- Module strikes the one that is ahead of it.

Further hazards are identified by NASA (Taylor *et al.* 2016).

There are many challenges to do with estimating the frequency with which these events occur. A starting point is to use industry experience and generic data bases. The data can then be analyzed using techniques such as fault tree and event tree analysis.

The next steps are to determine the level of risk associated with hazard and to determine if it meets the level of acceptable risk. This can be done using F-N curves, such as the following.



The sketch shows that there are three levels of risk:

- Acceptable;
- Area of judgment; and
- Unacceptable.

Safety Cases

One method of organizing a process safety program is to develop a 'Safety Case'. This is a document that is analogous to the "case" that an attorney will make in defense of his client in court following a serious incident. However, in this situation, the "case" is made *before* the event takes place.

Structure of a Safety Case

A Safety Case is a comprehensive document that, in principle, contains all the information and analysis that will allow the stakeholders to determine if the facility is safe. It is,

> *A documented body of evidence that provides a demonstrable and valid argument that a system is adequately safe for a given application and environment over its lifetime.*

Another definition, provided by the UK Ministry of Defence (MOD 2011) is:

> *A structured argument, supported by a body of evidence that provides a compelling, comprehensive and valid case that a system is safety for a given application in a given operating environment.*

Generally, at least three types of safety case are developed during a facility's lifetime: design, operational and eventual shutdown and termination of the operation.

Safety cases are prepared for all those who have an interest in the safety of the facility, including the facility's owners, managers, the public, employees and regulators. But the principal "customer" of a Safety Case is the organization that is actually operating the facility.

The Safety Case is not a static document sitting on a shelf. If management decides to make a significant change to the design or operation of the facility, then the Safety Case should be updated.

Basic Philosophy

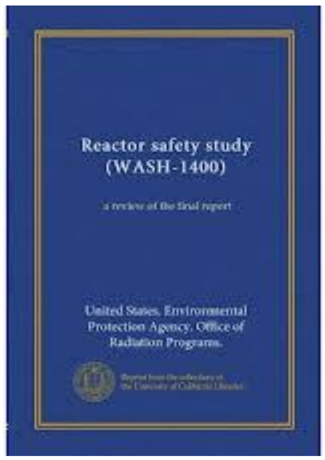
The basic philosophy behind Safety Cases is simple. Each system — in this case a hyperloop system moving passenger or freight pods from point A to point B — has a duty-holder. This is the company that owns and operates the facility after it has been built and is in operation. With regard to conventional railroads Amtrak and CSX would be typical duty-holders.

The duty-holder creates a Safety Case in order to satisfy *itself* that the system is safe. This is a crucial point; the Safety Case is not prepared for a regulator or the public — it is prepared by and for the entity that owns and operates the facility. Even if the duty-holder contracts out most of the design, construction and operation work, the organization is still responsible for the facility's safety. Other stakeholders such as the public are encouraged to participate in the development of the Safety Case, and the regulators will use for audits and assessments. But these organizations are not the primary clients.

The focus of most Safety Cases is on catastrophic events — events that could lead to loss of life or a major environmental release. The Safety Case may also be useful in improving occupational or "hard hat" safety issues such as trips and falls. But such is not its prime purpose — the principal aim is to understand and control the major hazards associated with complex industrial systems, such as hyperloop. The Safety Case must show that all major hazards have been identified and that the necessary precautions have been taken to reduce risk to an acceptable level.

Once the Safety Case has been prepared the duty-holder then implements the Safety Case Regime. This is the Safety Management System (SMS) that will be used to ensure that the day-to-day operations meet the standards set by the Safety Case.

WASH 1400



In the mid-1970s the civilian nuclear power industry was expanding rapidly. The principal safety concern to do with nuclear reactors is that they may suffer a runaway reaction of such intensity that the core melts down. The consequence of such an event would be disastrous.

In order to address this concern, the Nuclear Regulatory Commission authorized publication of the 'Reactor Safety Study' — often referred to by its subtitle, WASH-1400 (Rasmussen 1975). This study, which featured the use of probabilistic risk assessment (PRA), conducted a safety analysis of a generic nuclear power plant.

Generic Safety Case

The situation of the hyperloop industry is analogous to that of the nuclear power business two generations ago for the following reasons.

1. For both industries the basic technology is well developed and understood. However, it has not been fully commercialized. Inevitably the hyperloop business is going to run into unpleasant surprises, just as the nuclear power industry did. Incidents at Three Mile Island, Chernobyl and Fukushima-Daiichi illustrate that the risks to do with nuclear power were neither properly understood nor controlled.
2. Both industries are technically complex. The proper analysis and management of risk requires sophisticated modeling techniques, and the use of process safety management concepts.
3. They both have the potential to create a high consequence event. In the case of nuclear power, it is the release of radiation, for hyperloop it would be a module hitting the inside of the tube at high speed.

Therefore, it would make sense for the hyperloop industry to develop a generic safety report in the form of a Safety Case that uses the risk management principles that are an integral part of process safety management. Such a report would offer the following benefits.

- It would identify generic, high-risk issues that can be addressed well before any system enters commercial use.
- It can help choose between different design options.
- It would provide a useful "go-by" for companies as they develop their own safety programs.
- It would provide a basis for sensible regulations. (Although that does raise the question, at least in the United States, as to which federal agency would have the authority to issue such a report. Hyperloop is not a train, so it would not be the Federal Railroad Administration; hyperloop is not an airplane, so it would not be the Federal Aviation Administration; and hyperloop is not a road vehicle, so it would not be the National Highway Traffic Safety Administration.)
- It would provide a basis for those writing industry codes and standards.

Citations

Amazing Science. August 2014. World's Simplest Train. https://www.youtube.com/watch?v=J9b0J29OzAU.

Cullen, D. 1990. The Public Inquiry into the Piper Alpha Disaster. H.M. Stationery Office, London.

Earle, N. October 2017. 'A physical version of the Internet': How Hyperloop could be the broadband of transportation. McKinsey & Company.

MOD (UK Ministry of Defence). January 2011. An Introduction to System Safety Management in the MOD.

Musk, E. 2013. Hyperloop Alpha.

Rasmussen, N. 1975. WASH-1400 'The Reactor Safety Study'. Nuclear Regulatory Commission.

Sutton, I. July 2018. Hyperloop Safety Study. LoopTransPort 2018. HARP (Hyperloop Advanced Research Partnership).

Taylor C. *et al.* July 2016. Hyperloop Commercial Feasibility Analysis. NASA (DOT-VNTSC-NASA-16-01).