The Chernobyl Incident: A Case Study for Organisational Process Safety

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Over thirty years ago, Unit 4 in the Chernobyl Nuclear Power Station suffered what is considered the worst incident in the history of nuclear energy. In this paper we analyse the site and the organisation using modern-day process safety techniques—more precisely, what DEKRA calls Organisational Process Safety (OPS). It was found that OPS could have provided a clear picture of the process safety maturity of the organisation and, most important, of the interventions needed to improve it and therefore help prevent the incident. OPS builds on Process Safety Management (PSM), including the softer elements of Culture and Leadership. Its approach is applicable to those other sectors where PSM may be less established, such as food and pharmaceutical, which also have the potential for a catastrophe.

Organisational process safety, process safety management, culture, leadership.

Introduction

Over thirty years ago, Unit 4 in the Chernobyl Nuclear Power Station (ChNPS), in what was then the Ukrainian Soviet Socialist Republic and nowadays Ukraine, suffered what is considered the worst incident in the story of nuclear energy.

In this paper we attempt to analyse the process safety practices at the ChNPS using current tools and methodology. Specifically, using Organisational Process Safety (OPS), a new methodology created by DEKRA to support industrial organisations in their journey towards process safety excellence.

It is not the purpose of this paper to analyse the reasons for the incident (which can be found elsewhere). It is rather to check whether an OPS assessment could have provided some guidance on improving process safety at the station and, hence, helped prevent the incident.

Introduction to OPS

Strong process safety management is widely credited for reductions in major accident risk and improved industry performance with respect to catastrophic events that impact the health and safety of employees and other stakeholders. Process safety practices and formal safety management systems have been in place in most organisations for many years. Over the past 20 years, numerous government mandates for improved process safety performance have arisen, globally, which has prompted widespread implementation of a management systems approach to process safety management.

After an initial surge of activity, process safety management activities appear to have stagnated within many organisations. Incident investigations continue to identify inadequate management system performance as a key contributor to many incidents. Audits and regulatory inspections reveal a history of repeat findings indicating chronic problems whose symptoms are fixed repeatedly without effectively addressing the technical and cultural root causes.

The Center for Chemical Process Safety (CCPS) created what is recognised as a leading industrial approach on process safety management framework – Risk Based Process Safety (RBPS). The RBPS approach recognises that all hazards and risks in an operation or facility are not equal; consequently, apportioning resources in a manner that focuses effort on greater hazards and higher risks is appropriate. Using the same high-intensity practices to manage every hazard is an inefficient use of limited resources. A risk-based approach reduces the potential for assigning an undue amount of resources to managing lower-risk activities, thereby freeing up resources to address higher-risk activities.

DEKRA has streamlined the CCPS RBPS system, condensing the twenty elements into seven coordinated workstreams, as detailed in Table 1. The goal in this approach was to collect information for design of recommended high priority corporate-wide improvement projects related to process safety.

Table 1. Workstreams and CCPS elements

	Workstream	CCPS RBPS Element Name
1	Capability	• Compliance with Standards • Process Knowledge Management • Process Safety Competency • Training and Performance Assurance
2	Incident Response	• Stakeholder Outreach • Emergency Management • Incident Investigation
3	Risk Management	• Hazard Identification and Risk Analysis
4	Asset Integrity	• Asset Integrity and Reliability • Management of Change
5	Accountability	• Measurement and Metrics • Auditing • Management Review and Continuous Improvement
6	Operations	• Operating Procedures • Safe Work Practices • Operational Readiness • Contractor Management • Conduct of Operations – Operational Discipline
7	Culture and Organisation	• Process Safety Culture • Workforce Involvement

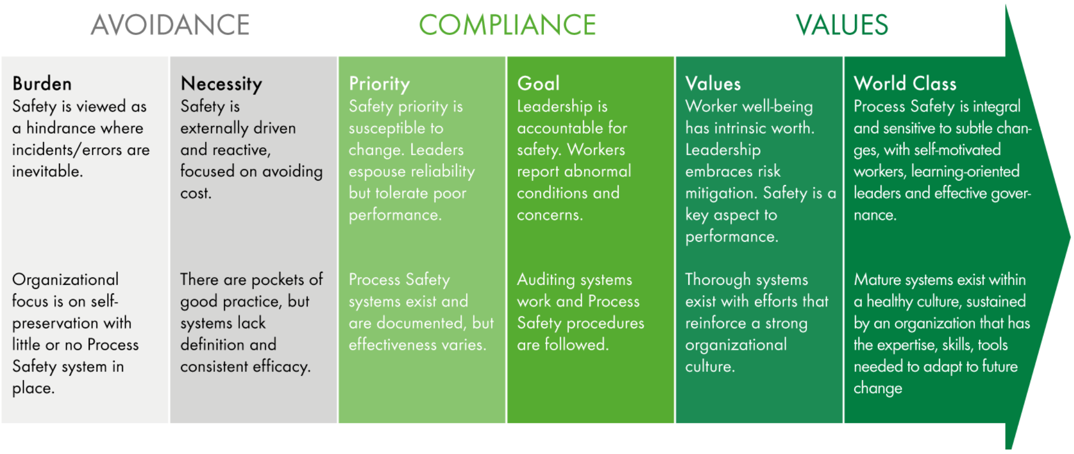
It must be pointed out that, despite "Culture and Organisation" being listed as a workstream just like the other six, a basic assumption of OPS is that this workstream deserves a special consideration, as it acts as the "glue" that holds together the entire system. It is also worth emphasising that these twenty elements and seven workstreams are not totally disconnected, as they have some strong interactions among them.

Another basic assumption of OPS is that you cannot know where you are and the things you need to do to improve, unless you also measure. This is a fundamental principle of science, beautifully summarised by Baron William Thomson Kelvin, in his lecture 'Electrical Units of Measurement', at the Institution of Civil Engineers, London, back in 1883:

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind : it may be the beginning of knowledge, but you have scarcely, in your thoughts advanced to the stage of science."

Any implementation will start, therefore, with an assessment. An assessment will obtain a picture of the current status and categorise each of the twenty elements of the process safety management in the site or organisation into one of the maturity levels shown in Figure 1

Figure 1. Maturity level scale.



Without getting into much detail, the assessment includes:

- A verification of the procedures, standards and registers documenting the process safety management of the site or organisation.
- A visit to the site during which a multidisciplinary team of experts perform different activities:
  - Observations of different elements of the plant that give a good representation of the process safety practices.
  - Face to face interviews with personnel at different levels of the organisation, including contractors. These interviews help also to determine the process safety practices but, most importantly, the culture at the site.

After completing these activities, the team of experts uses a scoring tool to determine the maturity level of the organisation in each of the seven workstreams and twenty elements. The scoring tool is based on a questionnaire for each element. Each question is scored from 1 to 4, based on the evidences observed in the documents provided and during the different activities at the site. The questions are chosen strategically to capture the key principles and essential features of each and every element. DEKRA has also developed very detailed scoring criteria to ensure consistency of results across teams of experts. Once all the questions of an element have been scored, the overall sum is mapped into the maturity level for this element.

The digital tool includes of course the questionnaire, scoring criteria and the algorithm for mapping into maturity level. Furthermore, the tool allows to keep all the information together and readily available for the scoring, including material provided by the client, as well that gathered during the site visit, notes, pictures or videos.

Additionally, the assessment will identify the interventions needed for the optimal progress in maturity. Furthermore, the assessment will rank the interventions in order to prioritise actions tending to improve “weak” elements over those actions intended to improve already “strong” elements. The assessment will identify tailored Key Performance Indicators (KPIs) that will allow monitoring of progress in the implementation until the next assessment.

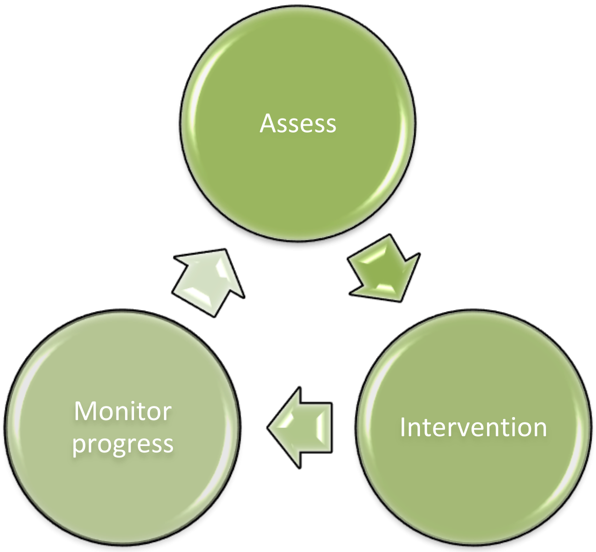
The OPS assessment methodology has been digitalised, thus allowing a very efficient workflow, from engagement with the site to delivery of results of the assessment.

The actions identified during the assessment need to be implemented by the organisation during the intervention phase, and the progress will be monitored using the KPIs identified in the assessment.

Finally, a new assessment will reset the picture to the new situation, thus starting the cycle again. The period between assessments is typically around two years and should never exceed five years.

The implementation of an OPS system is therefore a cyclic continuous improvement process, as shown in Figure 2.

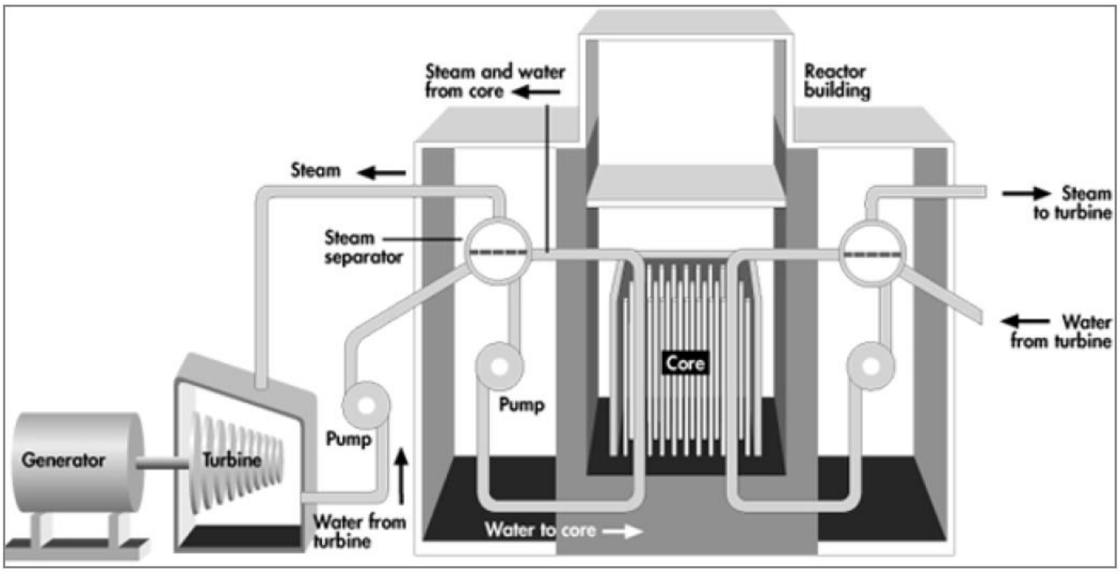
Figure 2. OPS implementation process



Brief description of the process at ChNPS

Figure 3 shows a very simplified scheme of the process in a RBMK[1] nuclear reactor.

Figure 3. Schematic of a RBMK reactor



Source: Nuclear Energy Institute, 1997.

RBMK is a boiling water design equipped with 1660 parallel vertical cooling channels (or pressure tubes). Each pressure tube can be loaded with a fuel element approximately 7 m long. The channels protrude vertically from a graphite block acting as neutron moderator. Each single channel can be isolated from the cooling water circuit by block valves.

The reactor is divided vertically in two identical halves, each one equipped with its own steam generation system. Each system collects water from a steam drum separator and pumps it through every power channel by means of four recirculating pumps (three in operation and one standing by at rated reactor power). Flow through each individual channel is controlled by means of valves. Water vaporises partially in the channels, thus extracting the energy generated at the fuel elements. The mixture of steam and water is collected at the top of the core and taken back to the steam drums. Dry steam from the steam

[1] RBMK is the acronym of *Reaktor Bolshoy Moshchnosti Kanalnyy*, or High Power Channel-type Reactor.

drums is sent to a turbogenerator, and turbine condensate is pumped back to the steam drum. The water/steam systems are, therefore, not that different from those of any thermal power station.

The control of the nuclear reaction is also not very different from a chemical batch reactor. One can consider that nuclear fission is a reaction between two reactants (neutrons and uranium-235). The reaction products include additional neutrons (more than one, on average) and significant amounts of energy. Left without control the reaction would run away immediately, as one of the "reactants" is multiplied by the reaction itself. To maintain a steady reaction rate, some control rods are inserted (to a higher or lower depth) in specific channels of the reactor. Control rods are made of a neutron absorbing material (boron) and therefore dispose of the excess neutronic "reactant". Control rods are also used to maintain the appropriate spatial distribution of the reaction rates as, unlike chemical reactors, RBMKs are not stirred at all.

There are two main systems to prevent runaways:

- All the control rods, as well some additional neutron absorbing rods, can be inserted immediately[2] into the core, thus "killing" the reaction.
- Even after stopping the reaction, the cooling of the core needs to keep going, as energy continues to be released by radioactive by-products. An independent emergency core cooling system is provided for this purpose.

In the early hours of Saturday, April 26th, 1986, reactor number 4 was undergoing a test. The sequence of operations during the previous day, combined with several design flaws and alleged violation of procedures by the operators, had put the reactor in a highly unstable state. At about 1:24 am, the attempt to shut down the reactor pushed the core into an unstoppable runaway in the form of a severe reactivity and power excursion. It is estimated that the runaway lasted for about 20 seconds. During this lapse, the power generated raised from about 0.2 GW to an estimated 300 GW. As a consequence, both the core and the enclosing building were damaged, exposing the unshielded heavily radioactive core to the environment, and starting a fire in the 1850 t graphite moderator block, further enhancing the dispersion of radionuclides in the atmosphere.

Out of the reported 237 people who suffered from acute radiation sickness, 31 died within three months of exposure. The long-term effects of increased exposure to ionising radiation are more difficult to assess, but they may range in the thousands if not tens of thousands of fatalities. Even today, a circle 30 km around the site is considered as hazardous to live in, and only inhabited by a few people who refused to relocate. The reactor building has been enclosed in a series of protective "sarcophagus". The inside of those structures is likely to be the deadliest area on planet Earth.

OPS diagnose of the ChNPS

Table 2 shows the summary of the results of the OPS assessment as applied to the ChNPS, while Figure 3 shows maturity levels of every workstream. As can be seen, every one of the elements and workstreams are scored according to the scale in Figure 1. It is important to understand, at this point, that appropriate process safety management is a complex issue that cannot be captured by just a scalar score. However, although organisations often like to be given an overall score, it would not be meaningful as can be clearly seen in Table 2: while some of the elements achieve reasonable maturity levels (e.g. asset integrity and reliability) others have ample room for improvement (e.g. operations discipline, process safety culture or workforce involvement).

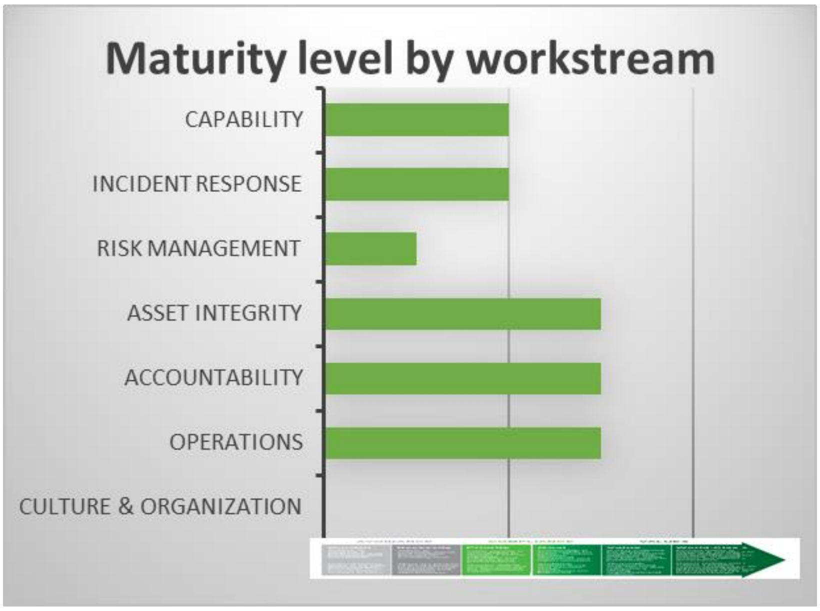
[2] It seems that insertion of control rods into the RBMKs was significantly slower than on western designs. This effect did play a role in the ChNPS incident.

Table 2. Results of the OPS assessment of ChNPS

DEKRA

#	Element	Score
	Workstream 1: capability	
1	Compliance with standards	4 Goal
2	Process knowledge management	2 Necessity
3	Process safety competency	4 Goal
4	Training and performance assurance	3 Priority
Total workstream 1		**3 Priority**
	Workstream 2: incident response	
1	Stakeholder outreach	3 Priority
2	Emergency management	4 Goal
3	Incident investigation	2 Necessity
Total workstream 2		**3 Priority**
	Workstream 3: risk management	
1	Hazard identification and risk analysis	2 Necessity
Total workstream 3		**2 Necessity**
	Workstream 4: asset integrity	
1	Asset integrity and reliability	4 Goal
2	Management of change	4 Goal
Total workstream 4		**4 Goal**
	Workstream 5: accountability	
1	Measurement and metrics	4 Goal
2	Auditing	4 Goal
3	Management review and continuous improvement	4 Goal
Total workstream 5		**4 Goal**
	Workstream 6: operations	
1	Operating procedures	2 Necessity
2	Safe work practices	4 Goal
3	Operational readiness	4 Goal
4	Contractor management	4 Goal
5	Conduct of operations-Operations discipline	1 Burden
Total workstream 6		**4 Goal**
	Workstream 7: culture and organization	
1	Process safety culture	1 Burden
2	Workforce involvement	1 Burden
Total workstream 7		**1 Burden**

Figure 4. Maturity level by workstream



The OPS digital tool provides many additional tables and charts, element by element and workstream by workstream. Benchmarking with other sites/organisations is also possible, after establishing a basis of comparison (business sector, geographical area…). These results:

- Allow the DEKRA experts to assess the current condition of process safety practice at the site/organisation.
- Provide a guidance in the design of an optimal roadmap for improvement.

Looking at Table 2 and Figure 4 above we can start drawing some interesting conclusions. Not surprisingly, the assessment detects low scores in the following elements:

- Process knowledge management.
- Incident investigation.
- Hazard identification and risk analysis.
- Operations procedures.

And especially low scores in:

- Conduct of operations-Operations discipline.
- Process safety culture.
- Workforce involvement.

It has been pointed out that, due to lack of both computing power and access to multigroup simulation codes, the USSR relied much on empirical data and even the use of non-nuclear pilot plants. It is clear that with these methods it is possible to acquire valuable information on steady state and routine operations, but it is unclear whether deviations that can lead to serious accidents can be simulated. Hence, the low scores in process knowledge management, hazard identification and risk analysis and operations procedures.

One of the key factors during the incident was the so-called positive void fraction coefficient: as the cooling water started to boil in the power tubes, the reactivity of the core increased. This, in turn, would vaporise more water, and further increase reactivity. This positive feed-back under very specific conditions (low power, heavily distorted neutron flux distribution, high burning degree of fuel) was well known to Soviet energy authorities. As a matter of fact, very similar runaway incidents, with much lesser consequences, occurred in Unit 1 of the Leningrad Nuclear Power Station (November 28^{th}, 1975) and in Unit 1 of the ChNPS (September 9^{th}, 1982).

It seems clear that a proper incident investigation, sharing of the lessons learned and incorporation of those into risk analysis and operational procedures would have helped to prevent the runaway at Chernobyl's Unit 4. Learning lessons from past incidents and near misses seems quite an obvious thing to do. Yet, this practice often has ample room for improvement in industrial practice. Sometimes incidents or near misses are not investigated properly and with the appropriate depth, thus missing the opportunity to identify the true root causes and draw conclusions; sometimes near misses are not investigated at all, due to resource constraints! In other cases, the information is not diffused in an adequate manner (sometimes cultural issues are at play; people often don't like to be exposed as "the one who had the incident"). Finally, in some cases the information exists, is published, but not incorporated. In other words, the lesson is there, but it is not learned.

Whatever the root causes, it is clear that a reliable system for drawing lessons learned from incidents and near misses at the site or the business at large is a key element in successfully managing process safety. ChNPS did not have this capability and, therefore, it can be identified as a clear need for improvement.

As it has been stated, OPS was built under the basic assumption that the relationship between Organisational Capability and Culture is the glue that integrates an effective risk management program. Not surprisingly, this assessment clearly identifies a very low safety culture maturity level in the organisation, which was almost unanimously identified as one of the root causes of the incident.

Of course, proposing a roadmap for improvement of the maturity level would require a deeper understanding of the organisation. Nevertheless, the OPS methodology immediately suggests some actions that need to be put in place for improvement:

- Identify and correct cultural issues that underlie the failure to fulfil process safety responsibilities (e.g. why the organisation is tolerating sub-standard performances?). Review periodically the process safety culture of the organisation.
- Establish a program to conduct risk analyses, audits, management reviews, and so forth in accordance with credible, established schedules.
- Establish a program to investigate incidents and near misses and guarantee their diffusion to all concerned persons.
- Establish appropriate operational procedures, including those for abnormal situations. Clearly define safe operational limits and require adherence to them. Ensure that those authorising deviations from standard procedures are well aware of the risks and have a sense of vulnerability.
- Encourage teamwork and open communication.
- Encourage workers to act deliberately and stop if conditions do not match their expectations. Train workers when to involve others in risk analyses. Train workers on how to recognise hazards, and how to recognise when unknown hazards may be present. Establish and promote an environment that encourages workers to develop a thorough understanding of their process.

Conclusions

DEKRA has developed Organisational Process Safety (OPS) as a methodology and digital tool to allow assessment and improvement of the process safety maturity of industrial sites and organisations. As a case study, the authors have applied an OPS assessment to the organisation of the Chernobyl Nuclear Power Station.

The OPS assessment has identified the strengths and weaknesses of the process safety practice at the site and organisation. Out of the twenty elements of the model, the lowest scores were assigned to:

- Conduct of operations-Operations discipline.
- Process safety culture.
- Workforce involvement.

The application of OPS has also allowed some specific actions to be proposed which are designed to improve maturity level of the site and organisation. These actions emphasise mainly cultural issues such as promoting open communication, empower personnel from a safety point of view, and establish and enforce risk-based operational procedures. Some additional technical actions, such as incident investigations and to perform risk analyses are also proposed.

Of course, the analysis could have yielded even better results if a complete assessment had been possible, including a visit to the site or face to face interviews with members of the organisation. However, even under these less than optimal circumstances, OPS proved its value by successfully identifying some important weaknesses in the process safety management system and practices at ChNPS and providing a roadmap for improvement. It is therefore clear that the implementation of the OPS approach along with the organisation implemented the actions, might have prevented or mitigated the incident.

References

Much has been written about the ChNPS incident. The authors chose to use the following references, deemed to be closest to the original sources:

- INSAG-7. The Chernobyl Incident: Updating on INSAG-1. A report by the International Nuclear Safety Advisory Group. International Atomic Energy Agency, Vienna, 1992. Especially relevant are the following two annexes:
    - Report by a Commission to the USSR State Committee for the Supervision of Safety in Industry and Nuclear Power. Causes and Circumstances of the Accident at Unit 4 of the Chernobyl Nuclear Power Plant on 26 April 1986 (Moscow, 1991).
    - Report by a Working Group of USSR Experts. Causes and Circumstances of the Accident at Unit 4 of the Chernobyl Nuclear Power Plant and Measures to Improve the Safety of Plants with RBMK Reactors (Moscow, 1991).
- NUREG-1250. Report on the Accident at the Chernobyl Nuclear Power Station. United States Nuclear Regulatory Commission. Washington, DC, 1987.
- Why INSAG has still got it wrong. Article by Anatoly Dyatlov (ChNPS's former deputy chief engineer, and witness of the incident). Nuclear Engineering International, 1995.

OPS being an in-depth assessment tool, it requires some pieces of information not readily available in the literature (understandably focused on the incident itself). Where needed, the authors made reasonable assumptions.