WHITE PAPER

The Chernobyl Incident: A Case Study for Organizational 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 analyze the site and the organization using modern-day process safety techniques–more precisely, what DEKRA calls Organizational Process Safety (OPS). We found that OPS could have provided a clear picture of the process safety maturity of the organization and, most important, of the interventions needed to improve it and therefore help prevent the incident.

Introduction

In the early hours of Saturday, April 26th, 1986, reactor number 4 at the Chernobyl Nuclear Power Station (ChNPS), in what was then the Ukrainian Soviet Socialist Republic (now Ukraine), was undergoing a test. The sequence of operations during the previous day, combined with several design flaws and an 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 reaction in the form of a sudden increase in reactivity and power excursion. It is estimated that the runaway reaction lasted for about 20 seconds. During this lapse, the power generated increased 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 enabling the dispersion of radionuclides into 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 ionizing radiation are more difficult to assess, but they may range in the thousands if not tens of thousands of fatalities. Even today, a 30 km circle around the site is considered hazardous to live in and is only inhabited by a few people who refused to relocate. The reactor building has been enclosed in a series of protective “sarcophagi”. The inside of those structures is likely the most hazardous area on planet Earth.

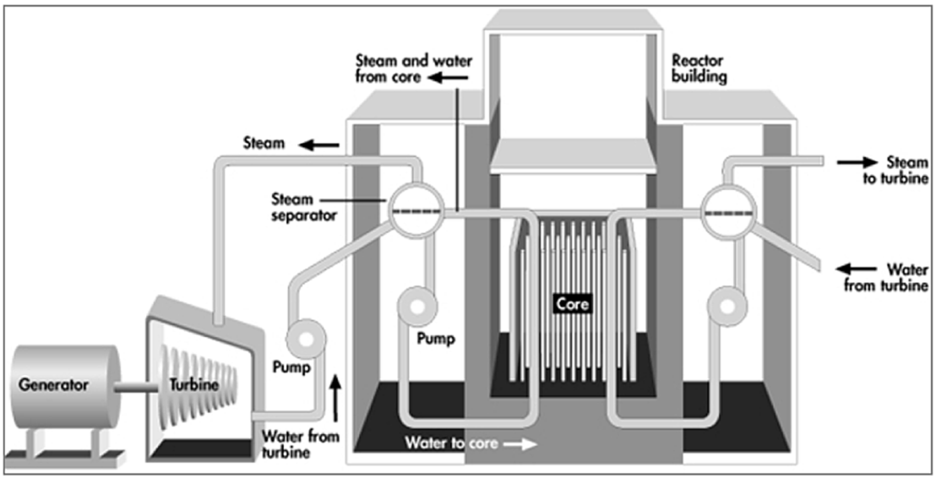

Figure 1. Schematic of a RBMK reactor (Nuclear Energy Institute 1997)

In this white paper we attempt to analyze the process safety practices at the ChNPS using current tools and methodologies, specifically DEKRA's own **Organizational Process Safety** (OPS), designed to provide a precise, repeatable and reproducible measure of process safety maturity. It is not our purpose to analyze the reasons for the incident at Chernobyl, which can be found elsewhere. Rather, we seek to determine whether an OPS assessment could have provided some guidance on improving process safety at the station and helped prevent the incident.

Our OPS methodology is constructed around guidelines created by the Center for Chemical Process Safety (CCPS) for chemical plants. In 1985, shortly after the chemical incidents at San Juan Ixhuatepec (Mexico) and Bophal (India), the American Institute of Chemical Engineers created CCPS, and tasked it with compiling a set of practices to improve process safety at chemical plants. The organization published its first guidelines (Guidelines for Technical Management of Chemical Process Safety) in 1989 and revisited them in 1992 and 2007. While the CCPS model was originally intended for the chemical industry, DEKRA OPS™ extends these concepts to other process industries.

At DEKRA we also strongly believe that the capability and culture of an organization constitute the foundation that supports all other elements of process safety management. OPS therefore places a very specific emphasis on the assessment of an organization's culture and capability. This combination of cultural and technical elements allows us to provide a sound roadmap for progression in process safety maturity.

RBMK Process Description

Figure 1 shows a very simplified scheme of the process in a RBMK[1] (Reaktor Bolshoy Moshchnosti Kanalnyy) nuclear reactor. 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 a 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). Valves control the flow through each individual channel. Water vaporizes partially in the channels, thus extracting the energy generated by 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 drums is sent to a turbogenerator, and turbine condensate is pumped back to the steam drum. The water/steam systems are, therefore, similar to any thermal power station.

The control of the nuclear reaction is also not very different from a chemical batch reactor. 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

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

DEKRA OPS **Workstream** Elements	**CCPS** Risk Based Process Safety Model **Elements**
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 Organization	> Process safety culture > Workforce involvement

Table 1. Workstreams and CCPS elements

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 runaway reactions:

- All the control rods, as well some additional neutron absorbing rods, can be inserted immediately[2] into the core, thus "killing" the reaction.
- An independent emergency core cooling system maintains cooling as energy continues to be released by radioactive by-products.

OPS Assessment

OPS groups the twenty elements of the CCPS process safety management model into seven workstreams, as shown in Table 1.

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

It must be pointed out that, while "Culture and Organization" is listed as a workstream just like the other six, a basic assumption of OPS is that this workstream deserves special consideration, as it acts as the "glue" that holds together the entire system. It is also worth emphasizing that these twenty elements and seven workstreams are not totally independent, as there are strong interactions among them. Another basic assumption of OPS is that organizations cannot understand their current status or what needs to be improved without reliable measurements. This is a fundamental scientific principle, beautifully summarized by William Thomson, 1st Baron Kelvin, in a lecture at the Institution of Civil Engineers back in 1833:

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

Therefore, OPS also defines a scale for maturity levels, as shown in Figure 2.

AVOIDANCE		COMPLIANCE		VALUES	
Burden Safety is viewed as a hindrance where incidents/errors are inevitable.	**Necessity** Safety is externally driven and reactive, focused on avoiding cost.	**Priority** Safety priority is susceptible to change. Leaders espouse reliability but tolerate poor performance.	**Goal** Leadership is accountable for safety. Workers report abnormal conditions and concerns.	**Values** Worker well-being has intrinsic worth. Leadership embraces risk mitigation. Safety is a key aspect to performance.	**World Class** Process Safety is integral and sensitive to subtle changes, with self-motivated workers, learning-oriented leaders and effective governance.
Organizational focus is on self-preservation with little or no Process Safety system in place.	There are pockets of good practice, but systems lack definition and consistent efficacy.	Process Safety systems exist and are documented, but effectiveness varies.	Auditing systems work and Process Safety procedures are followed.	Thorough systems exist with efforts that reinforce a strong organizational culture.	Mature systems exist within a healthy culture, sustained by an organization that has the expertise, skills, tools needed to adapt to future change

Figure 2. Maturity level scale.

Table 2 shows the summary of the results of the OPS assessment as applied to the ChNPS. As we can see, every one of the elements and workstreams are scored according to the scale in Figure 2. It is important to understand, at this point, that appropriate process safety management is a complex issue that cannot be captured by a single score on a scale. However much we would like to have a very simple "final score", it would not be meaningful as Table 2 makes clear: 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).

Figure 3 provides an alternative representation of the ChNPS results, showing the maturity levels of every workstream and highlighting one of the advantages our digitalized OPS assessment tool.

The assessment methodology is based on a questionnaire to be completed by DEKRA certified experts. Therefore, the OPS dashboard can offer results as detailed as Figure 4: percentage of questions in every maturity level category.

The OPS digital tool provides many different tables and charts, element by element and workstream by workstream. Benchmarking with other sites/organizations 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/organization.

> Provide guidance in the design of an optimal roadmap for improvement.

The tables and charts presented above, even without more extensive analysis, point to some interesting conclusions. Not surprisingly, the ChNPS 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.

Low scores in process knowledge management, **hazard identification** and risk analysis and operations procedures may be traced to a lack of computing power and access to multigroup simulation codes in the USSR. Instead, officials relied heavily on empirical data and even the use of non-nuclear pilot plants. With these methods, one can acquire valuable information on steady state and routine operations, but it is unclear that serious accidents can be simulated.

Element	Score
Workstream1: capability	
1 Compilance 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 Contarctor management	4 Goal
5 Conduct of operations-Operations discipline	1 Burden
Total workstream 6	4 Goal
Workstream 6: culture und organization	
1 Process safety culture	1 Burden
2 Workforce involvement	1 Burden
Total workstream 7	1 Burden

Table 2. Results of the OPS assessment of ChNPS

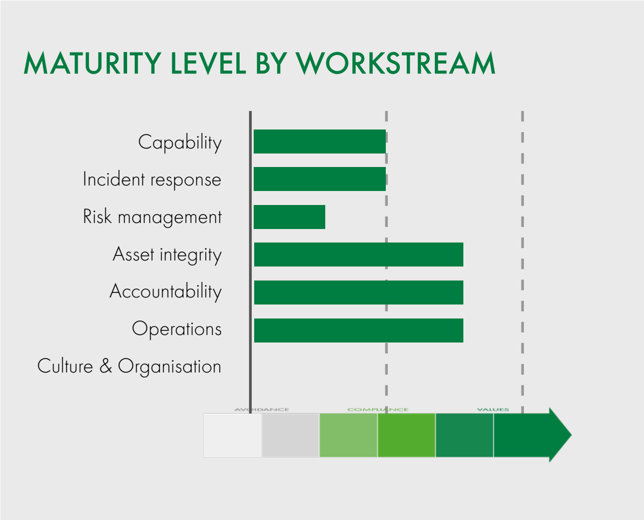

Figure 3. Maturity level by workstream

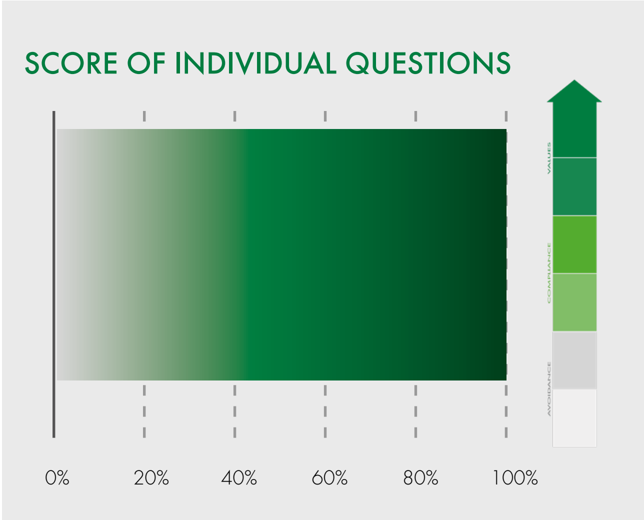

Figure 4. Percentage of questions in every maturity category

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 vaporize 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 28th, 1975) and in Unit 1 of the ChNPS (September 9th, 1982).

Clearly, proper **incident investigation**, sharing of lessons learned and incorporation of those into risk analysis and operational procedures would have helped to prevent the runaway reaction at Chernobyl's Unit 4. Deficiencies in these areas are not unusual in industrial practice. Sometimes incidents or near misses are not investigated properly and with the appropriate depth, preventing organization from drawing helpful conclusions, and sometimes near misses are not investigated at all, because of resource constraints. In other cases the information is not shared adequately, possibly as a result of cultural issues--people don't like to be exposed as "the one who had the incident." Finally, in some cases information is gathered and published, but not incorporated. In other words, the lesson is there, but it is not learned. Whatever the root causes, ChNPS was unable to successfully investigate, analyze and learn from the near misses that might have provided insight and prevented disaster.

Not surprisingly, our assessment clearly identifies a very low safety culture level at ChNPS, which has almost unanimously been identified as one of the root causes of the incident. It is not particularly surprising, since OPS recognizes that the relationship between organizational capability and culture is the glue that integrates an effective risk management program.

Of course, proposing a roadmap for improvement of the maturity level at ChNPS would require a deeper understanding of the organization. Nevertheless, the OPS methodology immediately suggests some actions required for improvement:

- Identify and correct cultural issues that underlie the failure to fulfill process safety responsibilities (e.g. why the organization tolerates sub-standard performance). Review the process safety culture of the organization periodically.
- 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 share investigation results with all those concerned.
- Establish appropriate operational procedures, including those for abnormal situations. Clearly define safe operational limits and require adherence to them. Ensure that those authorizing 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 recognize hazards, and how to recognize when unknown hazards may be present. Establish and promote an environment that encourages workers to develop a thorough understanding of their process.

Conclusion

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

The OPS assessment has identified the strengths and weaknesses of the process safety practices at the site and organization. Out of the twenty elements of the model, the lowest scores were in the areas of:

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

The application of OPS points to some specific actions designed to improve the maturity level of the site and organization. These actions emphasize mainly cultural issues such as promoting open communication, empowering personnel from a safety point of view, and establishing and enforcing risk-based operational procedures. Some more technical actions, such as investigating incidents and performing risk analysis are also proposed.

Of course, the analysis could have even better results if we could have done a complete assessment, including a visit to the site or interviews with members of the organization. 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 OPS 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 an 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.

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

DEKRA Process Safety

The breadth and depth of expertise in process safety makes us globally recognised specialists and trusted advisors. We help our clients to understand and evaluate their risks, and work together to develop pragmatic solutions. Our value-adding and practical approach integrates specialist process safety management, engineering and testing. We seek to educate and grow client competence to provide sustainable performance improvement. Partnering with our clients we combine technical expertise with a passion for life preservation, harm reduction and asset protection. As a part of the world's leading expert organisation DEKRA, we are the global partner for a safe world.

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