Lessons from the Chernobyl Nuclear Power Plant Accident for the Design of Organizational Improvement Initiatives

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Abstract: *This paper analyzes the design and functionality of the nuclear reactor, and the human failures on on-line operations, which had led to the accident at the Chernobyl power plant, in April 26, 1986. The paper finds that the combination of the Chernobyl-reactor characteristics and "freak infringements" of safety rules did cause the accident. The former aspect is due to the process of graphite-moderated uranium fission, which tends to increase in reactivity in the case of a malfunction or faulty operation. The latter is caused by the effect that infringements which did not cause accidents in the past lead to more violation of safety rules in the future. Transferred to organizational improvement programs, a corporation has to redesign its structure in the vein that failures cannot spread quickly (i.e. loosely coupled system elements), and to generate an atmosphere in order to encourage and utilize the full benefits of employees' participation.*

Introduction

"Good evening, comrades. As you all know, a misfortune has befallen us—the accident at the Chernobyl Nuclear Power Plant. [...] It goes without saying that [...] all the necessary conclusions will be drawn and measures will be taken to rule out a repetition of anything of the sort." (Gorbachev 1986: 514). With this speech given on May 15, 1986, Mikhail Gorbachev, the former general secretary of the Soviet communist party, admitted to the world the most severe accident in the history of the civil utilization of nuclear power. The west had already been well aware to that fact, since the radioactive fallout had reached Western Europe soon after the accident of April 26, 1986. Ironically, the accident happened during an experiment to improve the security of the reactor. If one looks on the extreme ends of a continuum of possible causes, there are two opposing explanations to the Chernobyl accident: one, primarily stressing the odd reactor design (Shulman 1993; Chernousenko 1991), and the other, mainly blaming the personnel of the reactor, e.g. the official report of the accident (for official and confidential reports, see Yaroshinska 1995; for a overview of the errors of the personnel, see Reason 1987). It becomes apparent that both factors played an important role in the occurrence of the accident. Thus, both are regarded in the following.

In his monograph "The Logic of Failure", *Dörner* considers "the immediate causes of the Chernobyl catastrophe, as psychological factors […] entirely." and he continues that "it was not more or less sophisticated technology that made the difference [in the accident] but—there's no other name for it—human failure." (Dörner 1996: 28–29). In the before-mentioned continuum of explanations to the accident, *Dörner* would therefore position near to the official report of the Soviet executives, as his view centers mainly on human failures on the stage of on-line operations. But *Dörner* is of course not as one-sided as the official Soviet report as *Dörner* analyzes the difficulties of decision makers, in generally, to estimate the consequences to their actions, if they are confronted with a complex system (or better, if they are a part of that system, see von Foerster 1985). In the official report, the complexity and design of the reactor did not play towards the disaster at all (but in the confidential reports, which were issued for internal usage of the Soviet executives, only; see Yaroshinska 1995; Chernousenko 1991). As will be shown in detail below, it makes a big difference to the controllability of a reactor, if it accelerates—e.g. after a loss of coolant—towards disaster, like the Chernobyl reactor did, or if it seeks to shut itself down. In the terminology of *Perrow*, such a system akin to the Chernobyl reactor is *complex* and *tightly coupled* (Perrow 1984): complex interactions are characterized by their unexpected and unplanned occurrences, which are either not visible or not immediately comprehensible. (*Perrow* terms the opposite *linear* interactions, as they occur in an expected sequence.) Furthermore, a system is termed *tightly* (antonym: *loosely*) coupled, if an accident is spreading quickly. Please note that these dimensions "complex–linear" and "tightly–loosely coupled" are sometimes addressed with the term "complexity", which has the dimensions variety, connectivity, and functionality (Milling 2002). In such a designed system, with a high number of elements, which are closely connected, and where the functionalities of those connections are nonlinear, trivial failures can end in severe accidents because such systems are *nontrivial* and hence unpredictable (Perrow 1984: chap. 2).

In order to address the issues raised so far, one has to develop a broader view on human failures than just on on-line operations. For this purpose, this paper observes different stages of human failure, i.e. (stage 1) planning and design of the socio-technical-environment, and (stage 2) on-line operations. The findings are then used to derive contributions to the design of quality improvement and preventive maintenance programs.

However, the aim of this paper is not to demonize or to promote nuclear energy in any way. People fear developing cancer due to nuclear radiation, while baking themselves in the sun during their summer holidays, which is clearly a non-rational assessment of risks. In addition, western style reactors behave completely different to Chernobyl-designed types, which "are like pressure cookers rattling on the stove" (Shulman 1993: 18). But on the other hand, one has always to be aware that "it is not possible for a technology to exist, to interact with human beings, and for there to be no inadvertent failures of the system or its operators." (Young 1997: 5). In addition, the aim of this paper is not to describe nuclear fission or the functioning of a nuclear reactor in every detail. Some figures and interrelations are estimated or simplified, respectively. But there is evidence that quantification, systems modeling, and simulation is useful in order to gain understanding of such systems even though empirical data is limited (Größler 2004). From there, the quantification and calibration is done with caution to the aspects of model validity. The interrelations and calibration of the more "technical" parts of the model are based mainly on the book "Insight from the Inside" from

Chernousenko, the former scientific director of the Chernobyl task force (Chernousenko 1991: chap. 3, appendix B), on general books on nuclear energy (e.g. Michaelis and Salander 1995: chap. 1, 2.2, and 6.2), and on other articles and reports on the causes of the accident (Malko 2002; Gorbachev 2002; Kiselev and Checherov 2001; Karisch 1996b; Birkenhofer 1996).

In a nutshell: the process of graphite-moderated nuclear fission

There are quite varying concepts of nuclear fission applied around the world. The reactors which are fueled with uranium classify either into *high* or *low-speed-neutron* types, mainly depending on the type of uranium in use. Natural occurring uranium consists of 0.006% ^{233}U, 0.7% ^{235}U, and 99.3% ^{238}U; but the latter isotope is much more likely to act as a neutron absorber without subsequent fission. As the reaction of ^{235}U is about 1000 times more efficient with thermal energy (*low speed*) neutrons than with fast (*high speed*) neutrons, natural occurring (or slightly enriched) uranium fuel is used along with some kind of neutron decelerator (*moderator*) elements. Moderators consist either of beryllium, graphite, normal or heavy water. In every fission a low speed neutron is absorbed which results in two fragments (barium and krypton) and 2 to 3 high speed neutrons (see figure 1). Part of the product neutrons continue the chain reaction, after being moderated, producing the next generation of neutrons, and part are either absorbed without inducing further fission or escape into the surrounding medium. In order to maintain the chain reaction, the number of neutrons produced must be greater than or equal to the number of neutrons that are absorbed, lost, and required to continue the chain reaction. The neutron multiplication coefficient *k* is defined as:

$$k = \frac{Neutrons_{\text{produced}}}{Neutrons_{\text{reactant}}} \ (1); \ k = k_{\infty} * L \ (2)$$

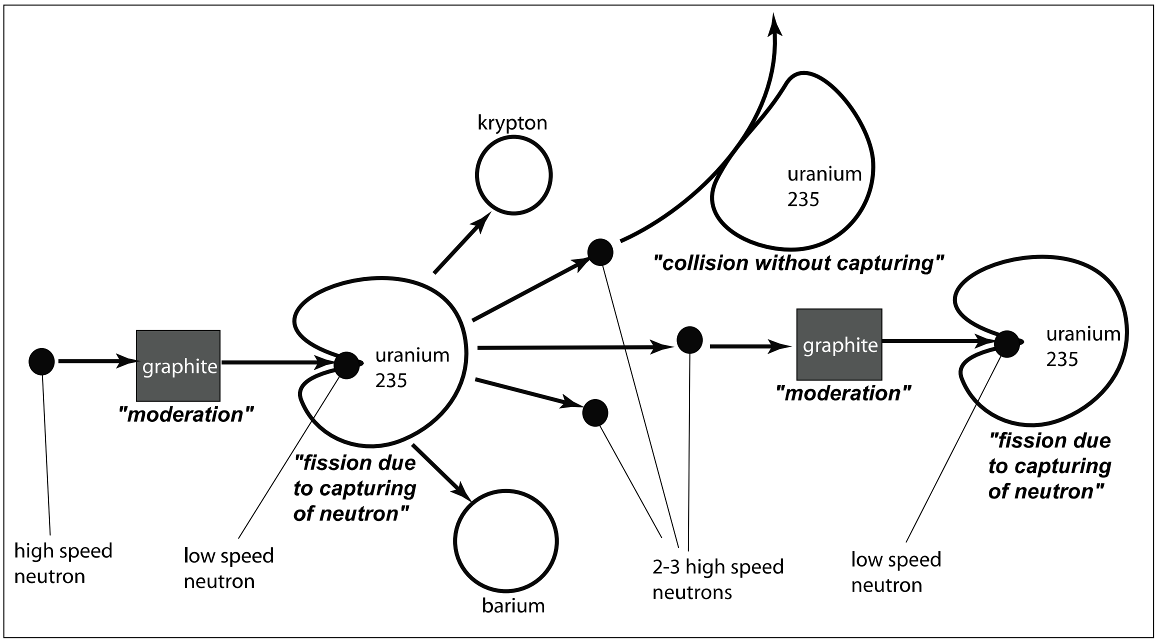

Figure 1: Graphite moderated chain reaction

The chain reaction is maintained, if *k*=1, the rate increases, if *k*>1, and the reactivity decreases and will eventually come to an end in the case *k*<1. The Ratio *k* depends mainly on two factors: the first is specific to the compensation of materials present in the core (*k-infinite*, k_∞), as some materials are more likely to act as an absorber than as a moderator, and the second depends exclusively on the geometrics of the reactor core (*L*). The latter factor of the equation (2) is therefore equal for all elements in the core. The first factor is very important to the neutron economy of a reactor, as e.g. graphite is approximately 1.4 times more efficient in the moderation of neutrons than normal water (see Michaelis and Salander 1995: table 1.11). Thus, the reactivity of the reactor may vary due to a change of composition of elements present in the core (e.g. ratio of graphite to water). Uranium has to be highly enriched in order to be useable as fuel with normal water as coolant and moderator. This is the case in all western light water reactors. However, this process of enrichment is quit expensive. In order to use natural or slightly enriched uranium one has to use heavy water (deuterium), which is also very expensive, or graphite as a moderator (Karisch 1996b). Figure 1 illustrates a graphite-moderated chain reaction as applied at the Chernobyl power plant.

Design and functionality of the Chernobyl reactor

The Chernobyl reactor was a RBMK-1000 ("reaktor bolshoi moshchnosti kanalnyi" [high-power channel reactor] with 1000 MW), which had been developed at the Soviet Technical-Energetically Research Institute at the beginning of the 1970s. The core of the RBMK has the form of a vertical cylinder with a diameter of approx. 12 and a height of 7 meters.

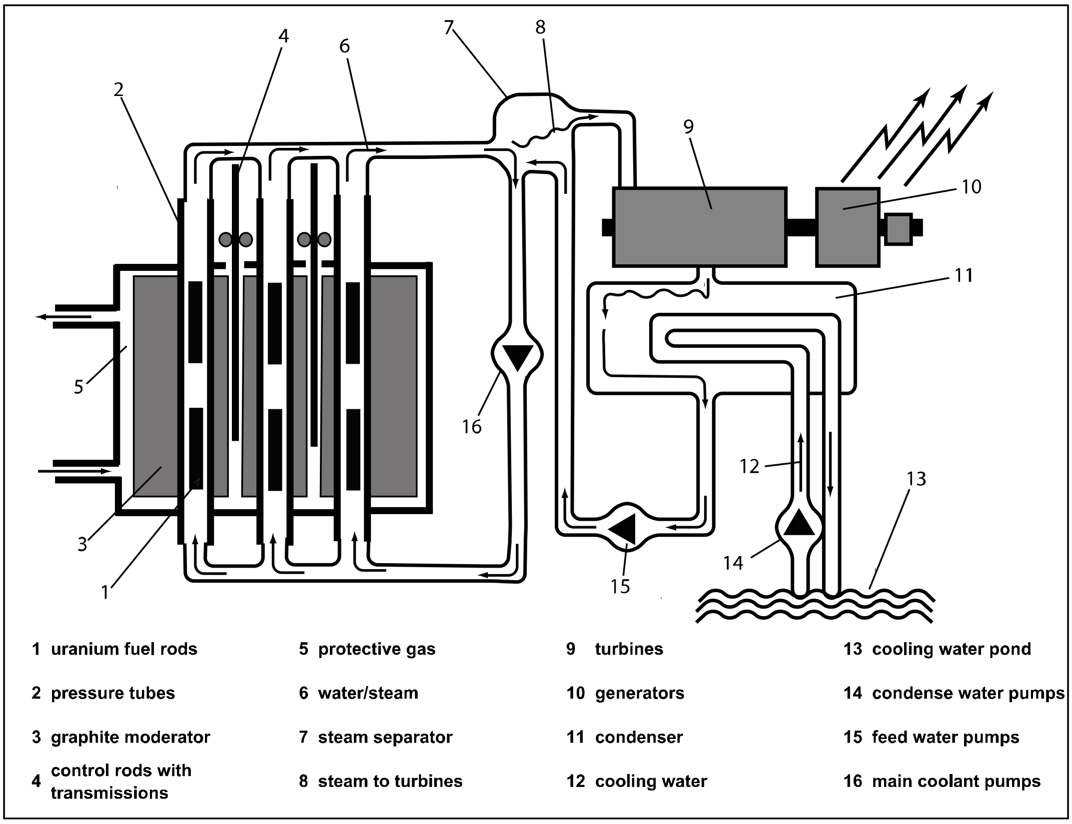

Figure 2: Construction of the Chernobyl nuclear reactor

The graphite moderator (3) is stacked as bricks in the core (see figure 2). These bricks are surrounded with protective gas (5) to protect them from oxidation, as graphite is a combustible material. Through the reactor core there are 1,661 pressure tubes (2), and each of it contains two uranium fuel rods (1). Water with a temperature of approx. 270° C and a pressure of 8.5 MPa enters each of the pressure tubes at the inlet at the bottom of the core. By passing the tubes the pressure of the coolant decreases to approx. 7 MPa and the temperature increases up to 285° C, which causes boiling of water. This steam-water mixture (6) flows into the steam separator (7), where it is separated into saturated water and steam. The latter is conveyed (8) through the turbines (9) in order to power the generators (10) and subsequently into the condenser (11). The condensed water (feed water) is then pumped (15) into the steam separator, where it is mixed together with the saturated water and is finally pumped (16) into the pressure tubes' inlets. The graphite-moderated neutron chain reaction, as illustrated in figure 1, is controlled by 211 control rods (4), which are made out of neutron absorbing elements (usually boron, cadmium or hafnium), and can be inserted and withdrawn from the reactor core.

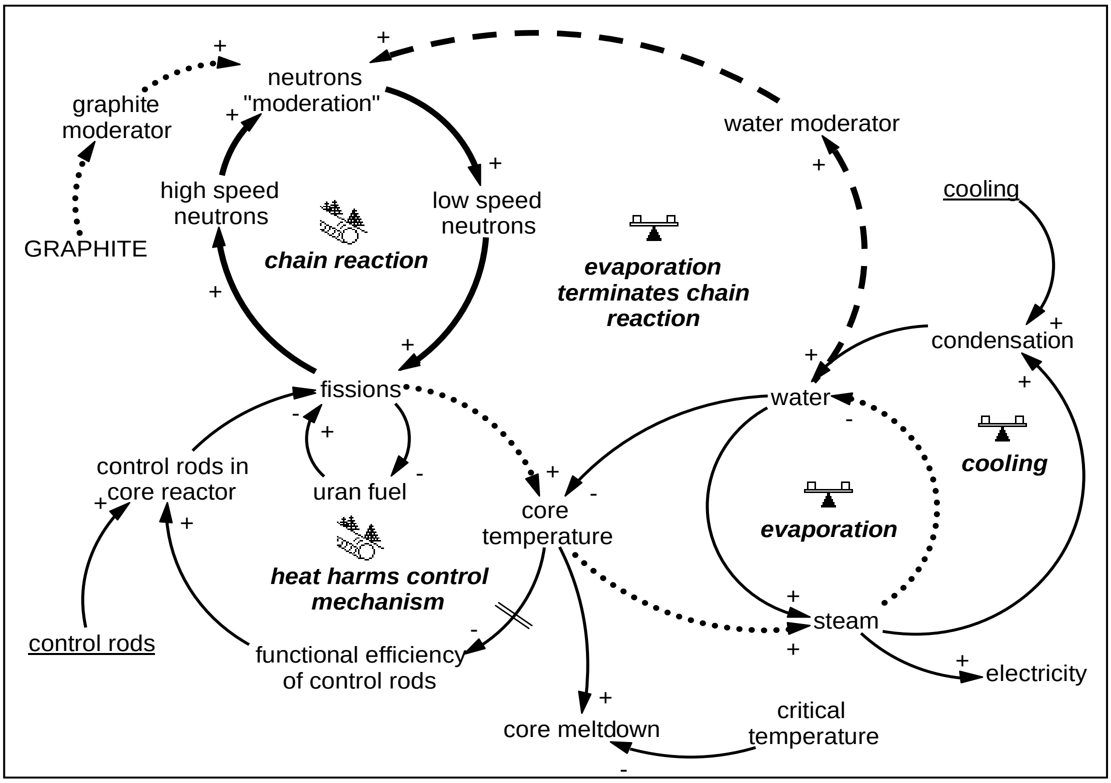

Figure 3: Basic functionality of a graphite moderated water cooled reactor

The functionality of the Chernobyl reactor is displayed in figure 3. The positive loop in the left upper part of figure 3 shows the before mentioned graphite moderated chain reaction: high speed neutrons are produced, some of them are absorbed, but some are moderated, and finally induce other fissions. Every fission event generates heat, which rises up the temperature of the coolant. Boiling of water increases steam, which is necessary to produce electricity in the turbines. In a water-moderated-water-coolant-reactor, like all western light-water-reactors, the chain reaction and the evaporation of the coolant put together imply an *intrinsic regulative* behavior. This is the case as water is needed to moderate the neutrons in the chain reaction and the chain reaction again generates heat, which itself evaporates water. Furthermore, water looses its ability to decelerate neutrons and is getting more likely to act as a neutron absorber, in the case of increasing water temperature (e.g. steam bubbles do not moderate as well as water).

In the case of Chernobyl, however, the opposite was the case. In a graphite-moderated-water-coolant-reactor reactivity increases, if core temperature increases or—which is the worst case scenario for such a reactor type—in the case of loss of coolant, e.g. after a steam explosion (see *moderation* in figure 4). This is because of the combination of a static moderation element (i.e. the graphite bricks) and a vaporizable moderation/coolant element (i.e. water): an increase in reactivity increases evaporation and this consequently lowers the amount of water present in the core. Lesser water means lesser cooling and, because this lowers the volume of water in comparison to graphite, higher reactivity. In the event of a water-moderated-water-coolant-reactor, evaporation or loss of water brings the chain reaction to an end. At a RBMK, in contrast, reactivity accelerates towards disaster in the case of loss of water, which means that the operators have lesser and lesser time to react.[1] The effects of such an accident in the coolant system are illustrated in figure 4.

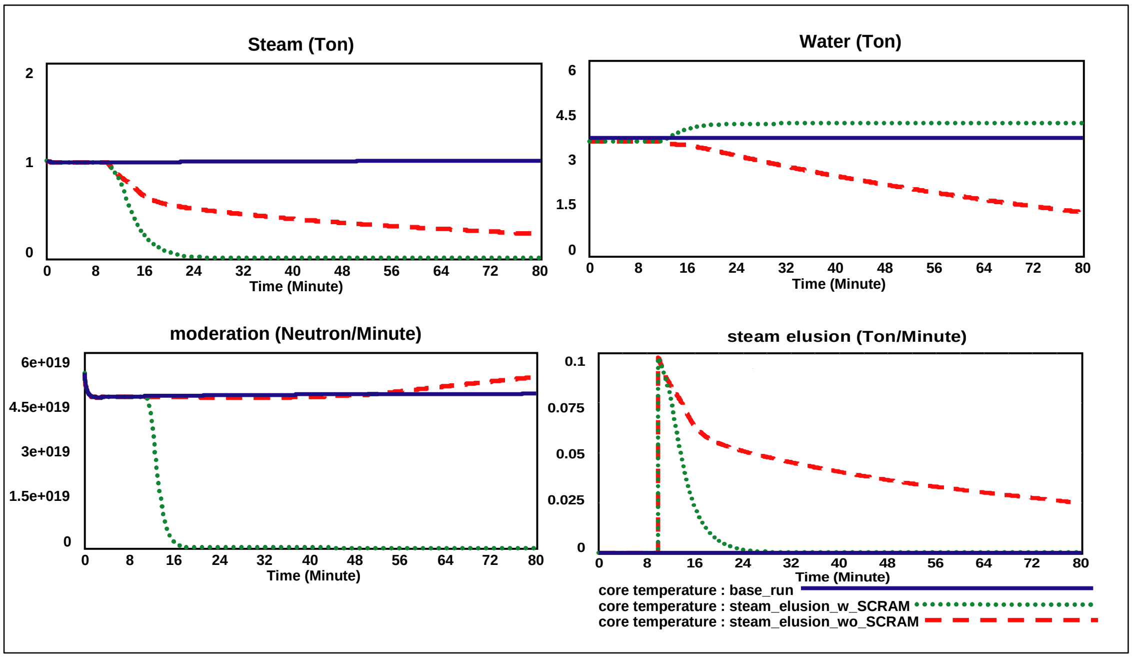

Figure 4: Simulation runs of normal operations and consequences of a steam explosion

Figure 4 shows the simulation runs of normal operations (*base_run*) and a steam explosion at the Chernobyl station (for the model see appendix A or folder A in the supplementary file). In the case of a steam explosion, steam is escaping fast, and because the core is still hot, evaporation is taking place yet, thus lowering the water present in the core. This leads to an increase of neutron moderation and therefore to an increase in fissions (see simulation run *steam_elusion_ wo_SCRAM* in figure 4). The dotted simulation run in figure 4 illustrates the situation, if the automatic emergency shutdown system (SCRAM) is functional and reacts immediately to the accident (*steam_elusion_w_SCRAM*). In this case the chain reaction will be terminated by insertion of all control rods (see *moderation*). This causes the core to cool down which leads to more condensation of steam than evaporation of water. In this case, only a part of the steam escapes and the water level is increasing in comparison to the base run. But as stated above, inadvertent failures at such complex and nontrivial systems are always possible to some degree, because the functionalities of the relationships between the system elements are ambiguous and therefore "safety systems may make it [even] worse" (Perrow 1984: 5)[2].

The situation with properly working SCRAM is not getting critical because there is still enough coolant in the core and the pumps are working properly. During the improvement experiment[3], on April 26, 1986, in contrast, the SCRAM-system had been shut off, the main pumps had been switched on manual control and nearly all of the control rods had been pulled out of the core by the operators. This is the second stage of human failure—i.e. online-operations—which played towards disaster in the Chernobyl accident, as *Dörner* describes it vividly. But, without the failures in design (first stage of human failure) that had been made beforehand, the Chernobyl incident might not have developed to such a disaster. It was the before mentioned increasing speed of reactivity that made the reactor hard to control and therefore increased the likelihood of human failure on on-line operations. Thus the characteristics of the Chernobyl reactor played a decisive role in the accident.

On-line operations

The experiment that led to the accident was a test of safety equipments which had been tried previously at both the Chernobyl-3 reactor and the Kursk station in Russia (Marples 1997)[3]. Thus, the personnel of the Chernobyl station were familiar with the experiment. The engineers at the Chernobyl plant had carried out such experiments to improve safety on a regular basis, like common at other potential dangerous facilities all over the world. The operators were experienced, too. As a matter of fact, the very same "highly respected experts [… who controlled the experiment…] had just won an award for keeping their reactor on the grid for long periods of uninterrupted service." (Dörner 1996: 33).

If neither the missing training respectively experience of the personnel or the lack of preventive programs to enhance the safety of operations were the cause for the accident, one might wonder why the system Chernobyl-4 did fail so badly. As shown in the paragraph above, the Chernobyl reactor was especially hard to control as its reactivity might develop exponential in the case of a malfunction or faulty operation. People have an inadequate understanding of exponential development. Thus, if failures arise, people tend to notice it too late or choose wrong retaliatory actions. But if people find it hard to control such exponential growing processes, why did the Cherobyl-4-operators switch the safety systems off and did control the reactor manually? The answer might be that they had done it frequently before, but with the important difference—of course—that the reactor never blew up. As *Dörner* puts it, "breaking safety rules is usually reinforced, which is to say, it pays off. Its immediate consequence is only that the violator is rid of the encumbrance the rules impose and can act more freely." (Dörner 1996: 31). Such a "flirting with disaster"-behavior has most of the time no negative consequences, as safety rules are usually designed with some margin of safety that prevents the violator from getting injured or harmed in any other way. These aspects are illustrated by the level-rate-diagrams in figure 5 and figure 6, which are parts of the same model (appendix B or folder B in the supplementary file).

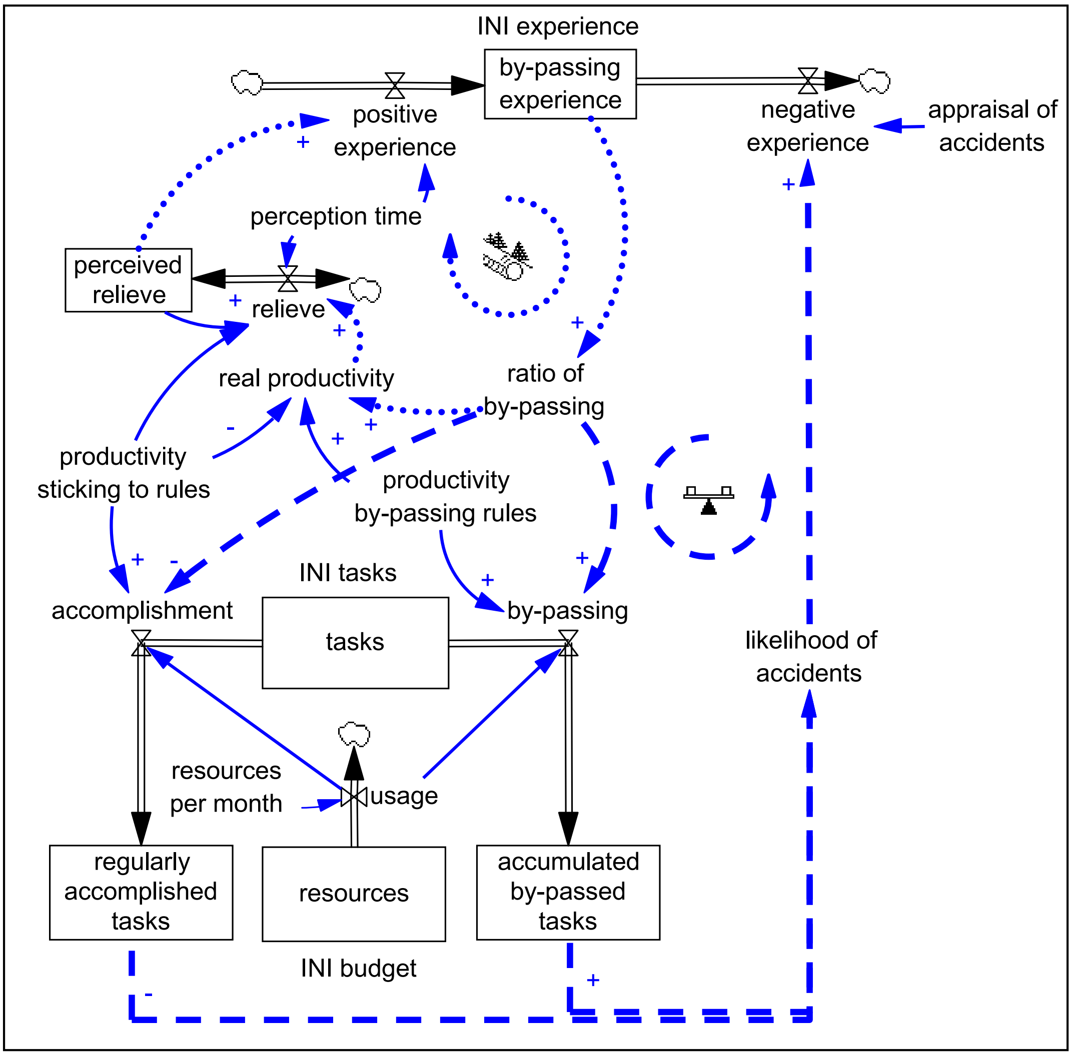

Figure 5: "Flirting with disaster"-behavior

The diagrams show a situation of an operator who has to accomplish a number of *tasks* with a certain limited amount of *resources*. The *perceived pressure* of the operator rises, if he has to accomplish more tasks than he believes is able to achieve with his *perceived productivity*. In this condition, the operator might tend to compensate pressure with violation of rules (the operator's bias towards by-passing of rules is embodied by the table-function *effect of pressure on by-passing* in figure 6). It is assumed that *by-passing* is twice more "productive" as *sticking to rules*. Thus, the operator perceives *relieve*, if he commits infringements. This *positive experiences* fuel the dotted, reinforcing feedback loop in figure 5, as *by-passing experiences* that did not end in accidents in the past lead to more *by-passing* of rules in the future. Such a "flirting with disaster"-effect can be stated as dangerous to an organization—not only to a nuclear power plant—as it potentially erodes the benefits of improvement programs, which might have been achieved beforehand.

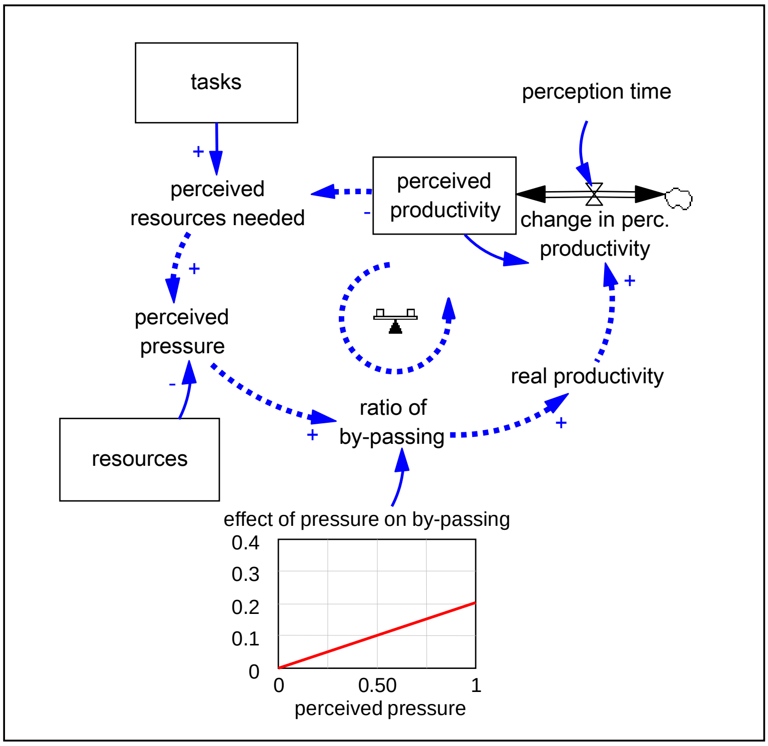

Figure 6: Pressure increases appeal to by-pass rules

As the Chernobyl accident shows dramatically, such a process cannot last forever, hence this effect is limited by the dashed feedback loop in figure 5: the *likelihood of accidents* depends on the tasks that are accomplished regularly in comparison to those, which are done by violation of safety rules. As can be seen in figure 7, an accident occurs at simulation time 85 which is lowering sequentially the "good" experiences, depending on the appraisal of the accident. In the situation with low or negative *by-passing experiences*, the operator stays strictly to the rules even though he perceives high pressure to accomplish his tasks. That is because he is working with care and attention which consequently lowers his perceived productivity.

Even if perceived pressure is only one possible reason out of many for violations of rules, it played an important role in the case of the Chernobyl accident, as the operators had been under pressure while undertaking the experiment. It is reported that the chief engineer Anatoly Diatlov did hurry up the operators to finish the experiment and to get the reactor back on the grid, just a few minutes before the core exploded ("Another 2 or 3 minutes and it will all be done. Cheer up, lads!", Karisch 1996a: 13–14). At this stage—approximately 15 minutes before the explosion—it should have been more than obvious to the operators that they are steering towards disaster, but they did not comprehend the situation fully resp. at all. This paper and the simulation experiments suggest two aspects as an explanation: the first is that the situation might have worsened very rapidly because of the reactor characteristics, as described above. One main attribute of nontrivial systems alike to the Chernobyl-reactor is that they do not give clear answers regarding their status to their controllers (Perrow 1984). Until now, it still is not clarified, if there had been any visual or acoustical warning, e.g. an alarm siren, during the accident (Chernousenko 1991). Thus, the operators might not have had a realistic chance to "control" the reactor because of invalid information. The second explanation is concerned about a possible bad safety culture, which might have biased the operators in such a way, that the operators were willing to take risks (second stage of human failure). If so, indeed “no one who should have stayed awake fell asleep [or] overlooked a signal that he should have seen. Everything the operators did they did consciously and apparently with complete conviction that they were acting properly.” (Dörner 1996: 34).

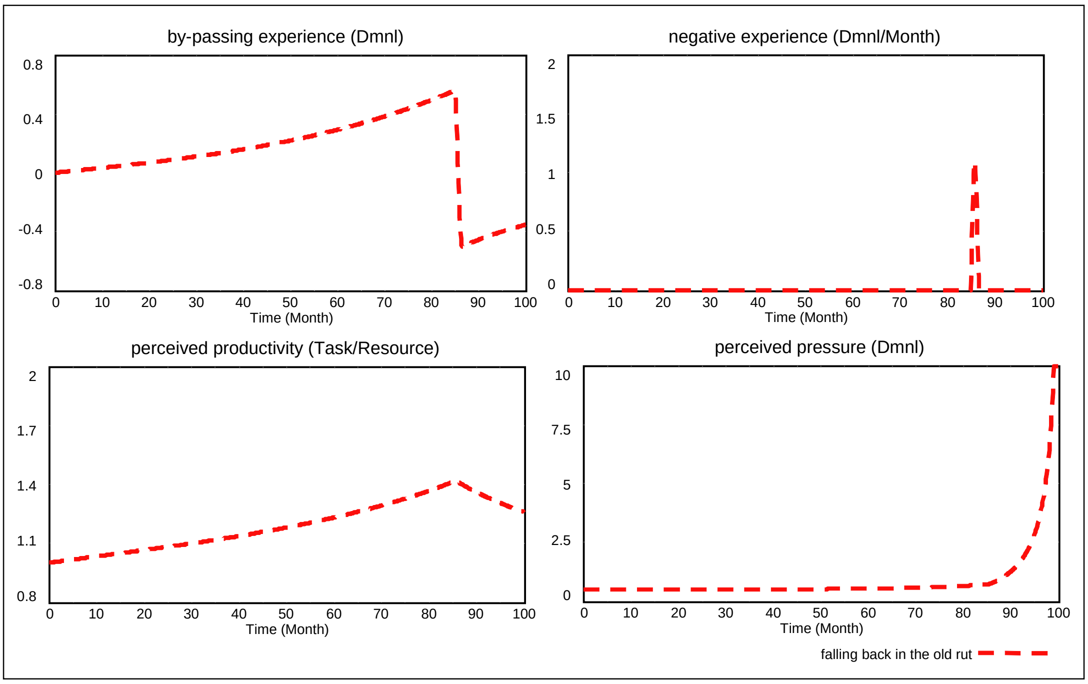

Figure 7: positive by-passing experiences lead to more violation of rules

Consequences for organizational improvement initiatives

In this section, the above stated findings on human failure are applied to organizational improvement initiatives, like quality improvement and preventive maintenance programs. The system thinking analyses and simulation runs highlight two different levels of human failure—i.e. (stage 1) planning and design of the socio-technical-environment and (stage 2) on-line operations.

Stein & Kanter (1993) analyze the Hubble fiasco, which exhibits some similarities to the stage 1 of human failure of the Chernobyl accident. They find that the Hubble fiasco is not “at its most fundamental level, a story about bad or even misguided people doing bad things; it’s a story about good people doing bad things.” (Stein and Kanter 1993: 60). According to them, the most important lesson to be learned is about how easy it is for an organization to convert good intentions to bad results and how common those effects are. In the Hubble case, the workers who used washers to shim the null connector lens had good intentions. They found a way to fix the problem they encountered in the most time-effective and least-cost way. The intentions were good—the results were disappointing.

The operators of the Chernobyl-4-station had good intentions, too, but the interesting aspect here is the conversion of good intentions into bad results. How did the structures of the NASA-Hubble-project-organization and the Chernobyl-reactor affect the workers that both systems did fail? *Stein & Kanter* find that the lessons learned "are not about weak managers and 'soul-less' organizations: they're about the damage of complex structures and the power of organizations and social systems to persuade well-meaning people to act in ultimately destructive ways." (1993: 60). According to them, attempts to "repair" structures by adding up dedicated control mechanisms in order to avoid every possible fault will only produce systems likely to fail in wider and less predictable ways. This results are in accordance with the findings on stage 1 of human failure, drawn in this paper (see also Perrow 1984). Such faulty structures require redesign to become more "robust" to variations.

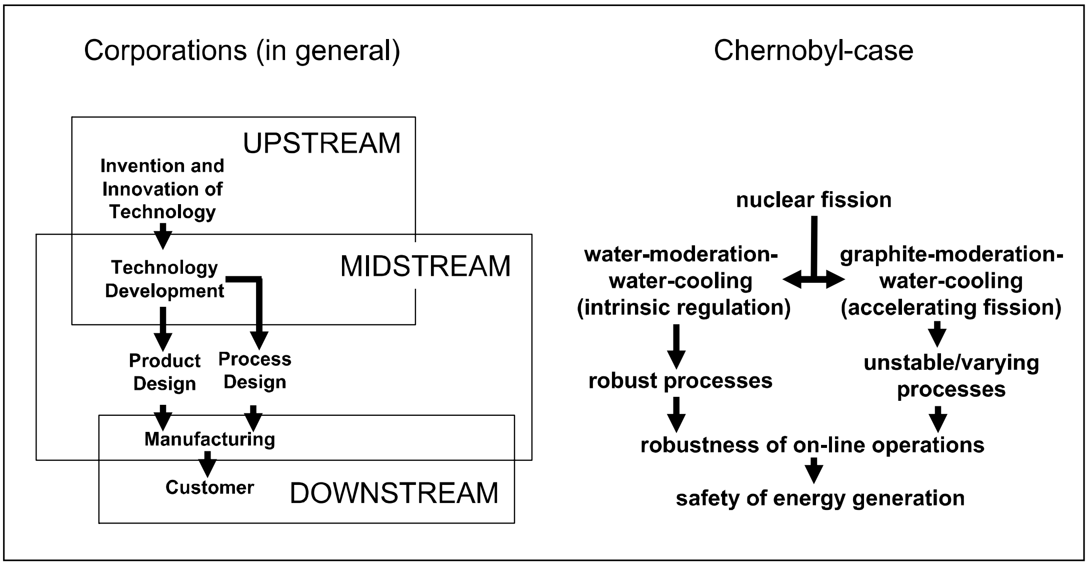

Figure 8: From invention to the customer—the view of Taguchi

One concept to improve "robustness" of the quality of processes and products is *Taguchi's* Quality Engineering (QE) (Taguchi and Clausing 1990). *Taguchi's* view on quality improvements is illustrated in the left side of figure 8 (Ealey 1992). *Taguchi* divides the process from invention to the customer in an upstream, midstream, and downstream part. The upstream section is the historical domain of western management, whereas the product and process design is the part, where Japanese manufactures are regularly good in. *Taguchi* states that it is important to be inventive and innovative (the western domain) but also to redesign technology and process that they are robust enough for real-world manufacturing (the Japanese domain) which is remote from the laboratory-conditions of the R&D-departments. If the last step is not accomplished, the corporations are forced to improve the robustness of their processes at the product level, which is much more difficult, time consuming, and expensive. A corporation that applies technology development is improving the underlying, generic technology itself instead of improving on a product-by-product basis. *Taguchi* denotes this with 'technology development'.

Therefore, the midstream part—especially technology development—is the crucial element in *Taguchi's* concept. The central difference between his concept and typical Western practices is a stage called "parameter design", during which engineers make the product or process "robust" against forces that cause variation. Most conventional Western techniques seek to control the external elements that cause variability. By contrast, QE focus on making the process itself robust against variation-causing elements. In an interview, *Taguchi* gives an example of a Japanese tile maker who encountered a problem with variations in the dimension of his tiles (Ealey 1992): the cause of variation was uneven heating in the kiln. Instead of buying a new kiln, the tile maker carried out parameter design experiments on the compound of the tiles. The parameter tests showed that adding limestone will reduce the effect. A new kiln would have driven up the costs without a guarantee of reducing the temperature effect. In *Taguchi's* view, quality is not about designing more and more "elaborated" technical systems, like the kiln, in order to control the process of manufacturing. It is about designing products and process through parameter design in such a way that they become robust enough to be produced with high quality.

The right side of figure 8 shows *Taguchi's* concept transferred to the Chernobyl-case: the upstream part is the appliance of civil nuclear fission, the midstream part is the decision whether graphite- or water-moderation-water-cooling nuclear fission should be used, and the downstream part is the robustness of on-line operations and the safety of energy generation. In analogy to the example of parameter design at the tile maker's plant, the usage of enriched instead of natural-occurring uranium fuel would have allowed the application of water-moderated nuclear fission, which implies intrinsic regulation (i.e. moderation increases evaporation, which on its part reduces moderation). Intrinsic regulative process allow for robust on-line operations, i.e. the process is robust to external variability (e.g. faulty operations by the personnel).

In contrast, the RBMK-reactor-design (i.e. graphite-moderation-water-cooling) generates unstable and varying processes, as the simulation runs illustrate in figure 4. As a consequence of the tight coupled system elements and the accelerating behavior of the Chernobyl-reactor, a failure in the coolant circulation (e.g. a steam explosion in the condenser) leads to an increase of reactivity in the core that again harms the control mechanism, which might end in a core meltdown. In this sense, defects create more defects and this effect might even increase in speed. In order to prevent an accident, one has to design an ultimate failsafe safety mechanism to control such an unstable process, which is literally impossible to accomplish. Instead of making the process robust on the level of the generic technology, as the QE-concept suggests, the RBMK-engineers tried to improve the safety of the reactor on the "manufacturing level", i.e. the on-line operations of the reactor. The consequence of such an improvement effort on on-line operations is exactly what this paper is all about: the Chernobyl nuclear power plant accident.

A corporation has to generate plans for redesign of its generic technologies or processes. In a tight coupled system as the Chernobyl reactor, however, it is cynical to blame misfortune as the cause for an accident ("a misfortune has befallen us") as such disasters are inherent to such a system. Apart from more technical aspects, the decisive role of redesign is true in a more organizational context, too; i.e. structuring which information is available in a corporation and to whom. "Too often, we see people in corporate positions repeatedly blamed for failure and replaced when the fault lies in the situation into which they have been put. Much of the time, it is the design of the organization that is defective." (Forrester cited in Keough and Doman 1992: 6-7).

The second part of this section regards stage 2 of human failure—i.e. on-line operations—and what can be derived especially to the design of preventive maintenance programs. The paper focuses on the interactions of operators and their technical environment, and therefore preventive maintenance initiatives are closely related to this case. In many preventive maintenance concepts, like Total Productive (TPM) or Reliability-centred Maintenance (RCM), autonomous maintenance is one of the cornerstones (Moubray 2000: chap. 13; Al-Radhi and Heuer 1995: chap. 4; Nakajima 1988: chap. 6; Gotoh 1989). Autonomous maintenance means that machine operators are responsible for "their" equipment. Therefore, operators are assigned to fulfill some basic maintenance tasks like lubricating, cleaning, monitoring etc. These simple tasks would be left over for the maintenance department, otherwise. Thus, this lowers the workload of the maintenance department (Thun 2004a; Thun 2004b; Maier 2000). The commitment of the operators to their equipment is also expressed by campaigns to improve tidiness and functionality of equipment, which ease planned maintenance and monitoring activities of the maintenance department. The monitoring tasks are important, as there is often little or no relationship between how long an asset has been in service and how likely it is to fail (Moubray 2000: chap. 7). However, although many failure modes are not age-related, most of them give some sort of warning that they are in process of occurring or are about to occur. Especially for failures, which are not age related, it is essential "to ask the right people—people who have an intimate knowledge of the asset, the ways in which it fails and the symptoms of each failure. For the most equipment, this usually means the people who operate it." (Moubray 2000: 165). It is apparent that a maintenance program cannot be beneficial with operators, which are caught in the "flirting with disaster"-routine, as described above. Thus, the cornerstone autonomous maintenance in combination with campaigns like 5 S-program and training of the operators, support the planned preventive maintenance activities of the maintenance department.

An additional example of an improvement program in which this "flirting with disaster"-attitude might be crucial is Six Sigma, where operators are urged to participate, too. Six Sigma is an information-driven "disciplined method of using extremely rigorous data gathering and statistical analysis to pinpoint sources or errors and ways of eliminating them." (Harry and Schroeder 2000). Therefore, data gathering and—of course—appropriate documentation is essential (Töpfer 2003). Inadequate gathering or documentation of data may not get apparent to the supervisors or the personnel immediately as it takes time to unfold its consequences. In contrast, the surplus workload of these activities is noticeable directly to the operators. In order to antagonize this effect so called "black belts" are established which are personally responsible for the quality of "their" processes. These black belts are trained in statistical and interpersonal skills so that they are able to moderate improvement projects with their co-operators (Caulcutt 2001). Even though they are specially trained and play an important role, they are not alike to ordinary supervisors as their status is normally limited to two years.

Another program with a similar pattern of personal responsibility, data gathering and small improvement projects which are accomplished by the operators themselves is Kaizen (Imai 1986), which origins are in Japan. Kaizen stands for a continuous improvement method that aims to balance process-oriented (e.g. number of team meetings, quality of documentation, number and quality of solutions, etc.) and result-oriented (e.g. scrap, machinery up-time, throughput time, etc.) goals. It is assumed that the latter key figures follow delayed on a decline of the former ones as these visualize the moral and motivation of the operators to participate in improvement initiatives. But it is very important to balance process and result-oriented goals as by overemphasizing the former the organization might not be able "to see the wood for the trees" and thus, not be able to achieve long-lasting strategies and innovations (Schaffer and Thomson 1992; Imai 1986).

To resume, for the design of organizational improvement initiatives, a corporation has to design its processes it applies on the level of generic technologies to avoid human failure on stage 1—i.e. that process are robust and thus failures cannot spread rapidly—and to apply initiatives to encourage employees' participation—like the latter programs—to avoid human failure on the second stage.

Conclusions and final remarks

This paper finds that in order to achieve a broader view of the Chernobyl accident and to gain contributions to the management of organizational improvement programs one has to look on human failures on (1) planning and design of the socio-technical-environment and on (2) human failures during on-line operations. The first is due to the characteristics of the Chernobyl reactor, i.e. that a failure will spread very quickly. This is a consequence of the process of graphite-moderated nuclear fission as had been applied in the Chernobyl reactor. This effect could have been eliminated by redesigning the process to water-moderated nuclear fission, which reacts with decreasing reactivity on increasing temperature and hence tends to shut itself down (i.e. *intrinsic regulation*). One concept to improve "robustness" of the processes is *Taguchi's* Quality Engineering (QE), which aims to target the underlying, generic technologies instead of downstream processes. It is obvious that redesign of equipment in order to decouple the consequences of failure is the most demanding part in an improvement program. In the case of the Chernobyl-reactor, redesign to water-moderated-fission means the construction of a completely new reactor. Beside this rather radical solution, there have been some other changes to the design of the equipment at the remaining RBMKs, which contributed to safety. E.g. the SCRAM has been redesigned to work faster and without the "rod-end effect" (Chernousenko 1991: 79)[2], and they are now fuelled with higher enriched uranium to reduce the positive void effect (that is, because enrichment increases the likelihood of a fission event and thus, less graphite is needed for the neutron economy of the reactor, see Michaelis and Salander 1995: chap. 6.2.4.3). Howsoever, all the latter "improvements" aren't likely to make the on-line operations of the RBMK-systems much more robust as the underlying process of nuclear fission is not robust to variation. It is apparent that the remaining RBMK-rectors have to be shut down as soon as possible.

The second cause of the reactor accident, i.e. human failure on on-line operations, is caused by the effect that seemingly "freak infringement of rules" (official Soviet report) which did not cause an accident in the past lead to more violation of rules in the future (Dörner 1996). Avoidance of this "flirting with disaster"-routine is quite demanding, too. Corporations need to establish a culture of safety and responsibility in order to encourage improvement programs like Total Productive (TPM), Reliability-centred Maintenance (RCM), Six Sigma or Kaizen. Particularly in Japan, approaches that emphasize personal responsibility and basic improvement initiatives at the workplace have become important. These activities have the potential to foster employees' participation but can become a pitfall also, in the case of high pressure on operators.

References

Al-Radhi, Mehdi, and Jörg Heuer. 1995. *Total Productive Maintenance. Konzept, Umsetzung, Erfahrung*. München/Wien: Hanser.

Birkenhofer, Adolf. 1996. Der Tschernobyl-Reaktor ist eine Fehlkonstruktion. In *Der Tschernobyl-Schock: Zehn Jahre nach dem Super-GAU*, edited by K.-H. Karisch. Frankfurt am Main: Fischer-Taschenbuch.

Caulcutt, Roland. 2001. Why is Six Sigma so Successful? *Journal of Applied Statistics* 28 (3&4):301-306.

Chernobyl Accident. World Nucelar Association 2004. Available from http://www.world-nuclear.org/info/chernobyl/inf07.htm.

Chernousenko, Vladimir M. 1991. *Chernobyl, Insight from the Inside*. Berlin; New York: Springer-Verlag.

Dörner, Dietrich. 1996. *The Logic of Failure: Recognizing and Avoiding Error in Complex Situations*. New York: Metropolitan Books.

Ealey, Lance. 1992. The 'Methods' of a Quality Master - An Interview with Genichi Taguchi. *McKinsey Quarterly* (4):3-17.

von Foerster, Heinz. 1985. Das Konstruieren einer Wirklichkeit. In *Die erfundene Wirklichkeit. Wie wissen wir, was wir zu wissen glauben*, edited by P. Watzlawick. München: Piper.

Gorbachev, Boris I. 2002. The Causes and Scenario of the Chernobyl Accident, and Radioactive Release on the CHNPP Unit-4 Site. Genshiryoku Anzen Kenkyu Group (Nuclear Safety Research Group, Japan).

Gorbachev, Mikhail. 1986. The Chernobyl Accident. *Vital Speeches of the Day* 52 (17):514-517.

Gotoh, Fumio. 1989. Autonomous Maintenance. In *TPM Development Program: Implementing Total Productive Maintenance*, edited by S. Nakajima. Cambridge, Mass.: Productivity Press.

Größler, Andreas. 2004. Quantification Makes Sense Even When Empirical Data Is Limited. In *Proceedings of the 22nd International Conference of the System Dynamics Society*, at Keble College, Oxford (UK).

Harry, Mikel J., and Richard Schroeder. 2000. *Six Sigma: The Breakthrough Management Strategy Revolutionizing the World's Top Corporations*. New York: Currency.

Imai, Masaaki. 1986. *Kaizen, the Key to Japan's Competitive Success*. 1st ed. New York: Random House Business Division.

Karisch, Karl-Heinz. 1996a. 'Da muß sich Furchtbares ereignet haben' Protokol der Atomkatastrophe von Tschernobyl. In *Der Tschernobyl-Schock: Zehn Jahre nach dem Super-GAU*, edited by K.-H. Karisch. Frankfurt am Main: Fischer-Taschenbuch.

———. 1996b. Krümelige Masse. In *Der Tschernobyl-Schock: Zehn Jahre nach dem Super-GAU*, edited by K.-H. Karisch. Frankfurt am Main: Fischer-Taschenbuch.

Keough, Mark, and Andrew Doman. 1992. The CEO As Organization Designer - An Interview with Professor Jay W. Forrester. *McKinsey Quarterly* (2):3-30.

Kiselev, A.N., and K.P. Checherov. 2001. Model of the Destruction of the Reactor in the No. 4 Unit of the Chernobyl Nuclear Power Plant. *Atomic Energy* 91 (6):967-975.

Maier, Frank H. 2000. Feedback Structures Driving Success and Failure of Preventive Maintenance Programs. In *Proceedings of the 7th International Conference of the European Operations Management Association: Operations Management: Crossing Borders and Boundaries: The Changing Role of Operations*, at Vlerick Leuven Ghent Management School, Belgium.

Malko, Mikhail V. 2002. The Chernobyl Reactor: Design Features and Reasons for Accident. Genshiryoku Anzen Kenkyu Group (Nuclear Safety Research Group, Japan).

Marples, David R. 1997. Nuclear Power in the Former USSR: Historical and Contempory Perspectives. In *Nuclear energy and security in the former Soviet Union*, edited by D. R. Marples and M. J. Young. Boulder, Colo: Westview Press.

Michaelis, Hans, and Carsten Salander. 1995. *Handbuch Kernenergie*. 4 ed. Frankfurt/Main: VWEW-Verlag.

Milling, Peter M. 2002. Understanding and Managing Innovation Processes. *System Dynamics Review* 18 (1):73-86.

Moubray, John. 2000. *Reliability-centered Maintenance*. 2 ed. New York, NY: Industrial Press.

Nakajima, Seiichi. 1988. *Introduction to TPM: Total Productive Maintenance*. Cambridge, Mass.: Productivity Press.

Perrow, Charles. 1984. *Normal Accidents: Living with high-risk Technologies*. New York: Basic Books.

Reason, James T. 1987. The Chernobyl Errors. *Bulletin of the British Psychological Society* (40):201-206.

Schaffer, Robert H., and Harvey A. Thomson. 1992. Successful Change Programs Begin with Results. *Harvard Business Review* 70 (1):88-89.

Shulman, Seth. 1993. Risky Reactors. *Technology Review* 96 (6):18-19.

Stein, Barry A., and Rosabeth M. Kanter. 1993. Why Good People Do Bad Things - A Retrospective on the Hubble Fiasco. *Academy of Management Executive* 7 (4):58-62.

Taguchi, Genichi, and Don Clausing. 1990. Robust Quality. *Harvard Business Review* 68 (1):65-74.

Thun, Jörn-Henrik. 2004a. The Dynamics of Maintenance - A System Thinking View of Implementing Total Productive Maintenance. In *Komplexität und Dynamik als Herausforderung für das Management*, edited by F. H. Maier. Wiesbaden: Deutscher Universitätsverlag.

———. 2004b. Modelling Modern Maintenance - A System Dynamics Model Analyzing the Dynamic Implications of Implementing Total Productive Maintenance. In *Proceedings of the 22nd International Conference of The System Dynamics Society*, at Keble College, Oxford (UK).

Töpfer, Armin. 2003. Six Sigma als Projektmanagement für höhere Kundenzufriedenheit und bessere Unternehmensergebnisse. In *Six Sigma: Konzeption und Erfolgsbeispiele*, edited by A. Töpfer. Berlin, Heidelberg et al.: Springer.

Yaroshinska, Alla. 1995. *Chernobyl, the Forbidden Truth*. Lincoln: University of Nebraska Press.

Young, Marilyn J. 1997. Introduction: Non-Rational Assessment of Risk and the Development of Civilian Nuclear Power. In *Nuclear energy and security in the former Soviet Union*, edited by D. R. Marples and M. J. Young. Boulder, Colo: Westview Press.

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[1] One might ask why the Soviet Union applied such a risky reactor design. One main feature of the Chernobyl reactor design was the ability to replenish single fuel rods without the necessity to shut-down the whole reactor, as in western style light water reactors (Marples 1997). This means that each fuel rod could be withdrawn separately when the concentration of plutonium-239 in the fuel rod had reached its optimum level for the production of nuclear weapons. But from this it follows also that the RBMK core as a whole could not be contained by one big vessel but out of over 1600 pressure tubes, which have to be controlled and cooled separately. In addition, there was no containment—i.e. a big ferro concrete dome with low air pressure inside to prevent escape of radioactive materials, which probably would have protected the environment to some extent. For example, at the accident at the Three Miles Island Unit 2, on March 28, 1979, the containment was robust enough to withstand several hydrogen explosions and consequently protected the population and the environment; even so it had been a very severe accident (Michaelis and Salander 1995, Chap. 6.2.4.2; Perrow 1984, Chap. 1). Instead of a

reactor vessel and containment, the Chernobyl core was only covered with a 1000 tons base plate, which had not been locked to the building and therefore could be lifted easily by pressures far less than 1 MPa (Michaelis and Salander 1995, Chap. 6.2.4.3). To resume, the RBMK reactor design provided two things, which the Soviet executives sought for: the production of plutonium to close the gap in the arms race against the United States while maintaining a high level of electricity output (Karisch 1996; Chernousenko 1991).

2 There is an ongoing debate whether the design of the control rods itself played an important role in the cause of the accident (e.g. Malko 2002; Birkenhofer 1996; Karisch 1996a; Karisch 1996b; Michaelis and Salander 1995; Chernousenko 1991). Riders respectively water displacers made out of graphite had been attached to the lower end of the control rods. When the control rod was in its uppermost position its tube would fill with water, which absorbs neutrons better than graphite. But from this it followed that the water displacing graphite riders could generate a burst of reactivity if they had been lowered in the core. ("to design a reactor with such an accident prevention system is equitant to designing cars in which, in a moment of need (for example, on a steep descent) the brake pedal becomes an accelerator." Chernousenko 1991: p. 76). Anyhow, this effect is not discussed any further in this paper or the models since this is a very specific characteristic of the Chernobyl reactor and does not show any behavior which is interesting in the view of system dynamics.

Another critical point was the amount of time needed to insert the rods. The period of 18 to 20 seconds was way to long for being useful for an emergency shutdown system. Soon after the Chernobyl accident the mechanisms at the remaining RBMK-reactors had been redesigned to react within 2 to 2.5 seconds (Chernousenko 1991; *Chernobyl Accident*, 2004).

3 The engineers of the Chernobyl plant were concerned about a problem regarding the emergency shutdown system of the reactor: in case of a sudden loss of electric supply, the pumps that circulate the coolant of the reactor core will stop. In such cases the automatic control system shuts the reactor down by pushing the automatic control rods into the core. However, the remaining heat of the core must be carried away further on to prevent the reactor of thermal damage. The electricity, which is necessary to operate the main circulating pumps in such an event, is generated by diesel generators that acquire some minutes for start-up. The engineers found the solution that they could bridge this time gap with the electricity generated by the slowing down turbines, as these will remain spinning due to their inertia for some minutes. In order to test this solution, the engineers had to steer the reactivity of the reactor down to mimic a shutdown.

Appendix A

```
********************************
Constants
********************************
ATOMS PER TON U235=
       2.56e+027
Units: Atom/Ton
Gives the number of atoms in one Ton of Uranium-235. (1000000 g = 1Ton;
Loschmidt-Number: 6.023e+023 Atoms per g; atomic weight of Uranium-235 = 235)
-> 10000000*6.023e+023/235

CHANGE IN REACTIVITY PER CONTROL ROD=
       0.05
Units: Dmnl/Rod
This figure bases on values out of table B.2. in Chernousenko (1991): one rod
lowers approximately the reactivity by 0.05% or 0.1 [beta]. Reactor
technicians use such tables in order to control reactor reactivity

"CONST: ratio of fission"=
       0.45
Units: Dmnl/Minute
The likelihood of a certain action between a neutron and an atom is defined
with the so called "cross section" [sigma]. U-235: scattering [sigma]-s=15;
absorption [sigma]-a=678 and fission [sigma]-f=577. The total cross section is
the sum over the three single values, [sigma]-t=1270, therefore the likelihood
of a slow neutron to induce fission is 577/1270 = 0.45 (approx.). For sigma
values, see Michaelis and Salander 1995, chap. 1.3.

COOLING EFFICIENCY=
       0.000342429
Units: Dmnl
this value is an approximation

DAMAGE POINT IN TIME=
       10
Units: Minute


DEGREE CELSIUS PER KJ=
       0.526316
Units: C/KJ


DESIRED CORE TEMPERATURE=
       270
Units: C
this is the normal operating temperature of the reactor

ELUSION TIME=
       10
Units: Minute
its assumed that steam eludes in the case of a broken condenser

ENRICHEMENT FAKTOR=
       1.8
Units: Dmnl
see Chernousenko 1991: table B.1.

"FISSION/NEUTRON"=
       1
Units: Fission/Neutron
ratio or fissions which are induced by one neutron
```

GOAL k=
1
Units: Dmnl
the chain reaction is maintained, if k=1, the rate increases, if k>1, and the reaction decreases, and will eventually come to an end in the case k<1.

GRAPHITE=
2
Units: Ton
amount of graphite in the core. figure is from Malko 2002

INI heating=
513
Units: KJ
Heat carrier temperature is 270 degree celsius (approx. 513 KJ) at reactor inlet (See Chernousenko, 1991: Table B.1. and Malko, 2002)

INI high speed neutrons=
5e+019
Units: Neutron
this variable is an assumption

INI low speed neutrons=
4e+019
Units: Neutron
this variable is an assumption

INI pumps=
6
Units: Pump
at normal circumstances, 6 pumps are switched on, 2 are only activated in case of emergency

INI rods=
22
Units: Rod

INI steam=
1
Units: Ton
this figure is an assumption

INI URANIUM LOAD=
192
Units: Ton
see Malko 2002; and Chernousenko 1991: table B.1.

INI water=
3.5
Units: Ton
this figure is an assumption

"KILO JOULES (th) PER FISSION EVENT"=
2.85714e-014
Units: KJ/(Fission)
3.15e+10 Fission obtain 1 Joule of power (figure taken form Chernousenko, 1991: 318). Therefore: 3.5e+13 Fissions = 1 KJ, or KJ per Fission is 1/3.5e+13

Minute=
1
Units: Minute

MXIMUM NUMBER OF PUMPS=
8
Units: Pump
There were 8 main circulating pumps: 6 for normal use and 2 as back-ups (Malko 2002)

"NEUTRON MULTIPLICATION COEFFICIENT (k-infinite): graphite"=
2.125
Units: Dmnl
this value is an approximation: graphie is approx. 1.35 times more efficient in neutrons moderation than normal water (see Michaelis, and Salander, 1995: table 1.11)

NEUTRONS RELEASE TIME=
0.15
Units: Minute

NORMAL PUMPAGE PER PUMP=
116.667
Units: Ton/Pump
figure is taken from Malko 2002: 15

NUMBER OF NEUTRONS PER FISSION=
2.5
Units: Neutron/Fission
figure taken from Michaelis and Salander 1995: table 1.8

PERCEPTION TIME=
1
Units: Minute

"REACTOR GEOMETRIC FACTOR (L)"=
1
Units: Dmnl
this value is an approximation

"RODS IN/OUT TIME"=
0.333334
Units: Minute
according to Chernousenko (1991) to bring in a control rod took approx. 18 to 20 sec

SPECIFIC EVAPORATION HEAT OF WATER=
2.26e+006
Units: KJ/Ton
To evaporate 1 gram of water one needs 2.26 KJ -> for 1 million grams (1 ton) one needs 2260000 KJ

STEAM EXPLOSION SWITCH=
0
Units: Dmnl
a steam explosion in the condenser is simulated in the case of "1"

SWITCH AUTOMATIC SHUTDOWN SYSTEM=
1
Units: Dmnl
SCRAM is switch on if the switch has value of 1, and off if value is 0.

TIME TO RUN UP PUMPS=
20
Units: Minute
this figure is an approximation

****
LookUps

```
********************************
T effect of number of rods(
             [(0,0)-(200,10)],(0,0),(200,1))
       Units: Dmnl


T effect of steam to condensation(
       [(0,0)-(1,1)],(0,0),(1,1))
Units: Dmnl
this variable assumes that condensation has decreasing economies of scales and
comes to an end in the case of vanishing steam

T effect of temperature on functional efficiency of control rods(
       [(0,0)-
(2,1)],(1,1),(1.75,1),(1.79816,0.962),(1.85627,0.85),(1.9419,0.477),(2,0))
Units: Dmnl
this value is an approximation: the more core temperature is rising towards
critical temperature, the more rods are being damaged

T effect of water to evaporation(
       [(0,0)-(1,1)],(0,0),(1,1))
Units: Dmnl
this variable assumes that evaporation comes to an end in the case of
vanishing water

T effect on pumps(
       [(0,0)-(1,1)],(0,0),(0.5,1),(1,1))
Units: Dmnl
this variable prevents that more pumps are switched on/off has than in place

T effekt of 235uranium on burning(
       [(0,0)-(1,1)],(0,0),(1,1))
Units: Dmnl
this variable assumes that burning has decreasing economies of scales and
comes to an end in the case of vanishing uranium-235

T likelihood for absorbation(
       [(0,0)-
(1,1)],(0,0),(0.192661,0.0338346),(0.400612,0.093985),(0.565749,0.18797),(0.68
1957,0.315789),(1,1))
Units: Dmnl

"T neutron multiplication coefficient (k-infinite): water (300°C)"(
       [(0,0)-
(10,1.5)],(0.6,0),(1.3,0.8),(1.8,1.2),(2.5,1.3),(3.6,1.4),(10,1.3))
Units: Dmnl
Graph is taken from Michaelis, and Carsten Salander, 1995: fig. 1.11

********************************
Auxiliaries & rates
********************************
absorption inducing fission=
       Low Speed Neutrons*ratio of fission
Units: Neutron/Minute
the rate of low speed neutrons captured by another uranium-235 core which
induce another fission

absorption or escape of high speed neutrons=
       max(High Speed Neutrons*(1-ratio of moderation),0)
Units: Neutron/Minute
number of high speed neutrons, which are not moderated. the maximum function
prevents this rate from being negative, which can happen in the case of a
"reactivity burst" that ends in a core meltdown

absorption or escape without further fission=
```

Low Speed Neutrons*(1-ratio of fission)
Units: Neutron/Minute
gives the rate of high low neutons per hour which are absorbed

burning=
T effekt of 235uranium on burning("235-Uranium")*neutrons released due to fission/ATOMS PER TON U235
Units: Ton/Minute

change of pumps=
intended change of pumps*T effect on pumps("Number of switched-on Pumps"/MXIMUM NUMBER OF PUMPS)*T effect on pumps("Number of switched-off Pumps"
/MXIMUM NUMBER OF PUMPS)/TIME TO RUN UP PUMPS
Units: Pump/Minute

change of rods=
functional efficiency of control rods*desired change of number of rods in core*T effect of number of rods(Number of Rods in Core
)*T effect of number of rods(
Number of Rods Withdrawn)/"RODS IN/OUT TIME"
Units: Rod/Minute

condensation=
cooling water flow*T effect of steam to condensation(Steam/INI steam)*COOLING EFFICIENCY
Units: Ton/Minute

cooling=
evaporation*SPECIFIC EVAPORATION HEAT OF WATER
Units: KJ/Minute

cooling water flow=
NORMAL PUMPAGE PER PUMP*"Number of switched-on Pumps"/Minute
Units: Ton/Minute
the flow rate from/to the cooling water pond

core temperature=
Thermal Power*DEGREE CELSIUS PER KJ
Units: C

desired change of number of rods in core=
-perceived gap in reactivity/CHANGE IN REACTIVITY PER CONTROL ROD*(1-perceived accident)+perceived accident*Number of Rods Withdrawn
Units: Rod
in normal operation mode, rods are adjusted according to the perceived gap of reactivity. in the case of emergency (perceived gap is bigger than zero) all the rods are inserted

evaporation=
heating*T effect of water to evaporation(Water/INI water)/(SPECIFIC EVAPORATION HEAT OF WATER)
Units: Ton/Minute

functional efficiency of control rods=
T effect of temperature on functional efficiency of control rods((core temperature)/DESIRED CORE TEMPERATURE)
Units: Dmnl

heating=
absorption inducing fission*"FISSION/NEUTRON"*"KILO JOULES (th) PER FISSION EVENT"
Units: KJ/Minute

```
intended change of pumps=
	(perceived temperature/DESIRED CORE TEMPERATURE-1)*"Number of switched-
on Pumps"
Units: Pump

k=
	neutrons released due to fission/(absorption inducing fission+
absorption or escape of high speed neutrons+ absorption or escape without
further fission
	)
Units: Dmnl
measure of reactivity: the chain reaction is maintained, if k=1, the rate
increases, if k>1, and the reaction decreases, and will eventually come to an
end in the case k<1.

likelihood for absorption=
	T likelihood for absorption("235-Uranium"/(INI URANIUM LOAD*ENRICHEMENT
FAKTOR/100))
Units: Dmnl

moderation=
	High Speed Neutrons*ratio of moderation
Units: Neutron/Minute
the rate of deceleration (moderation) of high speed to low speed neutrons

"neutron multiplication coefficient (k-infinite): water"=
	"T neutron multiplication coefficient (k-infinite): water
(300°C)"(volume ratio H2O over UO2)
Units: Dmnl

neutrons released due to fission=
	DELAY3I( absorption inducing fission*NUMBER OF NEUTRONS PER
FISSION*"FISSION/NEUTRON"*likelihood for absorption , NEUTRONS RELEASE TIME ,
absorption inducing fission*NUMBER OF NEUTRONS PER FISSION
*"FISSION/NEUTRON"*likelihood for absorption)
Units: Neutron/Minute
gives the rate of high speed neutrons per hour

perceived accident=
	smooth3( STEP(1, DAMAGE POINT IN TIME )*STEAM EXPLOSION
SWITCH,PERCEPTION TIME
	 )*SWITCH AUTOMATIC SHUTDOWN SYSTEM
Units: Dmnl

perceived gap in reactivity=
	GOAL k-"perceived reactivity (k)"
Units: Dmnl

"perceived reactivity (k)"=
	smooth(k, PERCEPTION TIME)
Units: Dmnl

perceived temperature=
	smooth(core temperature, PERCEPTION TIME)
Units: C

ratio of fission=
	max("CONST: ratio of fission"*(1-Number of Rods in Core*CHANGE IN
REACTIVITY PER CONTROL ROD/10),0)
Units: Dmnl/Minute

ratio of moderation=
```

```
      ("NEUTRON MULTIPLICATION COEFFICIENT (k-infinite):
graphite"*GRAPHITE/(GRAPHITE+Water)+"neutron multiplication coefficient (k-
infinite): water"
*Water/(GRAPHITE+Water))*"REACTOR GEOMETRIC FACTOR (L)"/Minute
Units: Dmnl/Minute
the overall moderation depends on the specific abilities of the core elements
to act as neutron absorber or moderator and their proportion of core elements
(see Michaelis and Salander 1995: chap. 1.3)

steam elusion=
      Steam/ELUSION TIME*STEP(1,DAMAGE POINT IN TIME )*STEAM EXPLOSION SWITCH
Units: Ton/Minute
this figure mimics a steam explosion with a lost of steam in two hours

volume ratio H2O over UO2=
      Water/"235-Uranium"
Units: Dmnl

********************************
Levels
********************************
"235-Uranium"= INTEG (
            -burning,
                  INI URANIUM LOAD*ENRICHEMENT FAKTOR/100)
      Units: Ton


High Speed Neutrons= INTEG (
      neutrons released due to fission-moderation-absorption or escape of high
speed neutrons,
            INI high speed neutrons)
Units: Neutron
the number of high speed neutrons in the reactor core

Low Speed Neutrons= INTEG (
      +moderation-absorption inducing fission-absorption or escape without
further fission,
            INI low speed neutrons)
Units: Neutron
the number of low speed neutrons in the reactor core

Number of Rods in Core= INTEG (
      change of rods,
            INI rods)
Units: Rod

Number of Rods Withdrawn= INTEG (
      -change of rods,
            211-INI rods)
Units: Rod

"Number of switched-off Pumps"= INTEG (
      -change of pumps,
            MXIMUM NUMBER OF PUMPS-INI pumps)
Units: Pump

"Number of switched-on Pumps"= INTEG (
      change of pumps,
            INI pumps)
Units: Pump

Steam= INTEG (
      +evaporation-condensation-steam elusion,
            INI steam)
Units: Ton
```

```
Thermal Power= INTEG (
       heating-cooling,
              INI heating)
Units: KJ

Water= INTEG (
       condensation-evaporation,
              INI water)
Units: Ton
```

Appendix B

```
********************************
Constants
********************************
appraisal of accidents=
             10
       Units: Dmnl

FINAL TIME  = 100
Units: Month
The final time for the simulation.

INI budget=
       101
Units: Resource

INI experience=
       0.1
Units: Dmnl

INI tasks=
       150
Units: Task

INITIAL TIME  = 0
Units: Month
The initial time for the simulation.

perception time=
       30
Units: Month

"productivity by-passing rules"=
       2
Units: Task/Resource

productivity sticking to rules=
       1
Units: Task/Resource

resources per month=
       1
Units: Resource/Month

switch=
       0
Units: Dmnl
"switch"=1 means that "perceived pressure" does not play a role,thus any
increase in "by-passing experience" is generated by feedback and started by
"INI experience". "Switch"=0 means that "INI experience" is zero and the
dynamics is increased by "perceived pressure".

TIME STEP  = 0.125
Units: Month
The time step for the simulation.

********************************
LookUps
********************************
"effect of pressure on by-passing"(
             [(0,0)-(1,1)],(0,0),(1,0.2))
```

```
       Units: Dmnl


********************************
Auxiliaries & rates
********************************
accomplishment=
              productivity sticking to rules*usage*(1-"ratio of by-passing")
       Units: Task/Month

"by-passing"=
       "productivity by-passing rules"*usage*"ratio of by-passing"
Units: Task/Month

"change in perc. productivity"=
       (real productivity-perceived productivity)/perception time
Units: Task/(Resource*Month)

likelihood of accidents= WITH LOOKUP (
       XIDZ( "accumulated by-passed tasks", regularly accomplished tasks, 0),
              ([(0,0)-(1,1)],(0,0),(0.9,0),(1,1) ))
Units: Dmnl/Month

negative experience=
       appraisal of accidents*likelihood of accidents
Units: Dmnl/Month

perceived pressure= WITH LOOKUP (
       perceived resources needed/resources,
              ([(0,0)-(10,10)],(0,0),(1,0),(2,1),(10,10) ))
Units: Dmnl

perceived resources needed=
       tasks/perceived productivity
Units: Resource

positive experience=
       perceived relieve/perception time
Units: Dmnl/Month

"ratio of by-passing"=
       max("by-passing experience",0)*switch+(1-switch)*max("by-passing
experience"
+"effect of pressure on by-passing"(perceived pressure),0)
Units: Dmnl
"switch"=1 means that "perceived pressure" does not play a role, thus any
increase in "by-passing experience" is generated by feedback and started by
"INI experience". "Switch"=0 means that "INI experience" is zero and the
dynamics is increased by "perceived pressure". the max-function is necessary
as "by-passing experience" is allowed to get negative after an accident.

real productivity=
       productivity sticking to rules*(1-"ratio of by-passing")+"productivity
by-passing rules"
*"ratio of by-passing"
Units: Task/Resource

relieve=
       ((real productivity-productivity sticking to rules)/productivity
sticking to rules
-perceived relieve)/perception time
Units: Dmnl/Month

usage=
       resources per month
```

```
Units: Resource/Month

********************************
Levels
********************************
"accumulated by-passed tasks"= INTEG (
             "by-passing",
                    0)
      Units: Task

"by-passing experience"= INTEG (
      +positive experience-negative experience,
             INI experience*switch)
Units: Dmnl
"switch"=1 means that "perceived pressure" does not play a role, thus any
increase in "by-passing experience" is generated by feedback and started by
"INI experience". "Switch"=0 means that "INI experience" is zero and the
dynamics is increased by "perceived pressure".

"effect of pressure on by-passing"(
      [(0,0)-(1,1)],(0,0),(1,0.2))
Units: Dmnl

perceived productivity= INTEG (
      "change in perc. productivity",
             productivity sticking to rules)
Units: Task/Resource

perceived relieve= INTEG (
      relieve,
             (real productivity-productivity sticking to rules)/productivity
sticking to rules
)
Units: Dmnl

regularly accomplished tasks= INTEG (
      accomplishment,
             0)
Units: Task

resources= INTEG (
      -usage,
             INI budget)
Units: Resource

tasks= INTEG (
      -accomplishment-"by-passing",
             INI tasks)
Units: Task
```