# THE DYNAMIC ANALYSIS OF THE CHERNOBYL ACCIDENT

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## ABSTRACT

The scenario of the Chernobyl accident is introduced. Based on that scenario, the point reactor kinetics equations are used to obtain the dynamic analysis of the accident. The power variation during the accident is analyzed and calculated. Learned lessons and recommendations are provided to prevent or mitigate similar future accidents in the nuclear power stations.

## INTRODUCTION

The two worst accidents in the world's nuclear industry occurred in a time span of seven years, are those occurred at Three Mile Island Nuclear Station Unit 2 (TMI-2) in 1979 and at Chernobyle in 1986. Evaluation of these accidents revealed that human errors involved in maintenance and operation phases could be major contributors to accidents [1].

Hence the risks of reactor accidents are not only plant specific (dependent on design) but also time specific (dependent on the competence of the plant operation and maintenance). A simplified conceptual fault tree of an accident Figure (1), illustrates that either a maintenance failure or an operating error could cause an accident [2]. The figure shows that equipment failures can be reduced by using passive design features that reduce the need of maintenance. Also, the operation errors can be reduced by simplifying operator actions in operations by use of automated controls.

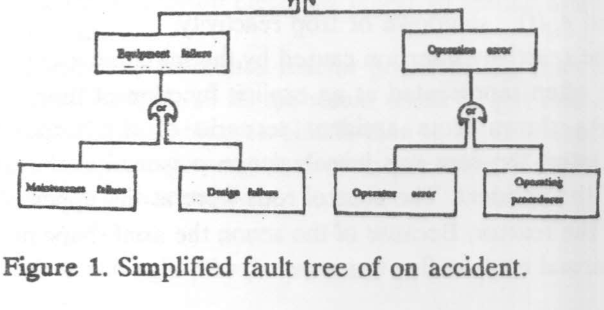

Figure 1. Simplified fault tree of on accident.

Many publications [2-5] describe and analyze the consequences of the Chernobyl accident to extract lessons for improving designs, safety systems and procedures in the nuclear power plants.

In this paper the Chernobyl accident scenario is introduced. Based on that scenario, the accident dynamic analysis is developed using the point reactor kinetics equations. The power variation during the accident is calculated and discussed. The learned lessons and recommendations are provided to prevent or mitigate the future accidents in the nuclear power stations.

## THE CHERNOBYL REACTOR (RBMK-1000)(UNIT 4)

The core of RBMK reactor [5] consists of a huge container, filled with graphite blocks. As shown in Figure (2), the blocks are pierced by about 1660 vertical holes, in which the pressure tubes and the control rods. Water is pumped from the bottom of the pressure tubes over the fuel. It removes the heat from the fuel, turns to steam, and leaves the reactor core at the top. From there it goes through pipes and gives up its energy to spin two large turbines, in an adjacent building. The turbines in turn spin electrical generators, and cooled water goes back into the reactor core again. All the reactor itself does is the mundane job of boiling water.

As in all pressure tube reactors some of the heat produced by the uranium (about 5%) leaks out to thee moderator. The heat flows slowly from the graphite back through the pressure tubes, and is finally taken away by the boiling water. Now the problem with graphite at high temperature is that it operates at a high temperature, about 700°C,and if exposed to air, it will burn slowly. So it is very important in the RBHK design to keep air away from the graphite. To do this, the entire core is put in a sealed metal container Figure (3), and mixture of inert gases, helium and nitrogen, which do not react with graphite, is circulated inside the container. The container is built so it could withstand the failure of a pressure tube without bursting and letting in air. The rest of the structure shown in Figure (3) is just shielding, to reduce the levels of radiation around the reactor while it is operating. On the sides of the RBMK reactor there are shields made of water, sand, and concrete. On the bottom and top there are concrete shields. All the pressure tube and control rods are attached to the top shield which had been played a key role in the accident.

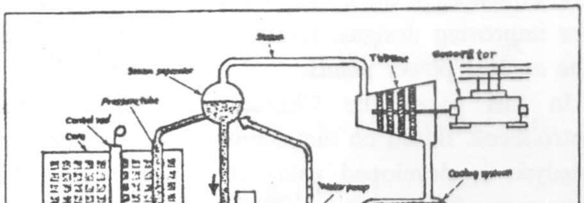

Figure 2. Schematic diagram of the RBMK-1000

Chernobyl unit 4 reactor had shutdown and emergency core cooling systems, but had only a partial containment. The pipes below the reactor core are installed inside "leaktight boxes". These boxes are connected to a huge pool of water under the whole reactor building. If one of the pipes in the boxes breaks, the steam would be forced into the pond, where it and any radioactive particles it contains would be trapped in the water, and the leaktight boxes would hold. All the steam pipes above the core are installed inside ordinary industrial buildings Figure (4). Thus if one of these pipes breaks,, particularly in the case of large breaks, a release of radioactive steam would occur. The main design features and the physical characteristics of Chernobyl unit 4 reactor are listed in Table (1) [5].

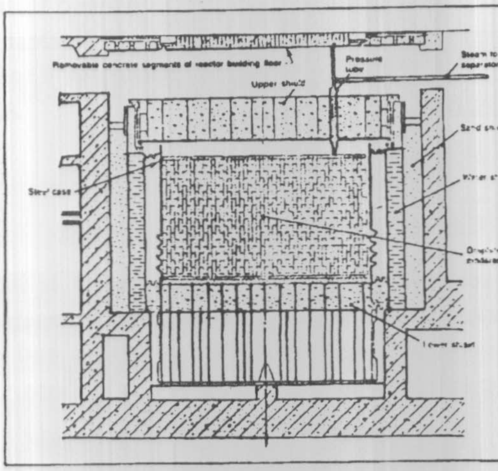

Figure 3. Cross sectional view of reactor vault.

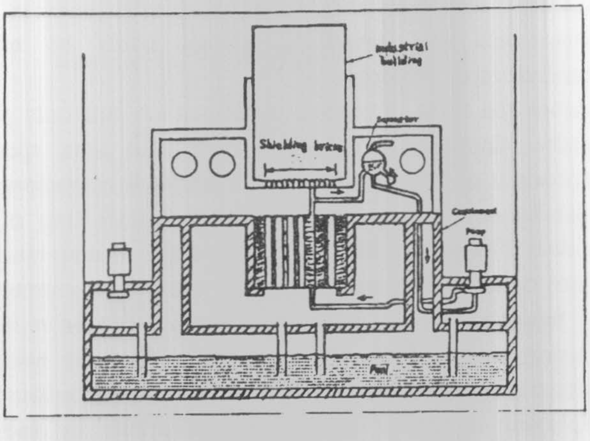

Figure 4. Chernobyl containment.

$\rho_{fb}(t)$ reactivity from thermal-hydraulic feedback,

$\rho_c(t)$ reactivity from the reactor power control system,

and $\rho_{sd}(t)$ shutdown or trop reactivity.

The reactivity insertion caused by the initiating event may be often represented as an explicit function of time.

As shown from accident scenario of the Chernobyl reactor, the core was heavily xenon poisoned at the time of the accident. The control rods were at the upper edge of the reactor. Because of the xenon the axial shape of the thermal neutron flux was unusual, with high flux at the top and bottom and a depression in the center. If the reactor power had been constant or changing slowly, most of the steam would have been at the top of the channels because steam builds up axially toward the top. In that case, the greatest flux increase during the excursion would have been at the top because the water is displaced by steam, which captures fewer neutrons, and many fission neutrons can leak to the axial graphite moderator and be thermalized. However, the control rods are also in this zone, and, being in a high thermal neutron flux area, would have been very effective. So the flux increase probably occurred near the bottom of the core where there was nothing to stop it.

Table 1. Chernobyl Design Features

| | |
|---|---|
| Coolant | Ordinary Water |
| Steam cycle | Direct (Steam & Water from reactor are separated and steam goes directly to turbines) |
| Fuel | 2% enriched uranium oxide |
| Moderator | Graphite bricks (max temp. 700°C) |
| Fuel channels | Vertical, pressure-tube, no calandria tube. |
| **Safety Systems** | |
| Containment | No upper containment Lower containment is concrete cells surrounding high pressure piping & connected to water pool, to reduce the building pressure. |
| Shutdown | One mechanism: Absorber rods 10 seconds to be effective, Effectiveness depends on state of plant. |
| Emergency Core Cooling | High pressure injection<br>Driven by gas and pumps, then pumped flow. |

## THE CHERNOBYL ACCIDENT SENARIO [5]

The accident of April 26, 1986 started during the conduction an experiment to see how long a spinning turbine could provide electrical power to certain systems in the plant.

The idea was to reduce reactor power to less than half its normal output, so all the steam could be put into one turbine. The remaining turbine is then to be disconnected where its spinning energy is used to run some of the main pumps for a short while.

Table 2. Chernobyl Accident Sequence.

| Time | Event | Comments |
|---|---|---|
| April 25<br>01 : 00 | Reactor at full power<br>Power reduction began. | As planned. |
| 13 : 05 | Reactor power 50 %<br>All steam switched to one turbine. | As planned. |
| 14 : 00 | Reactor power stayed at 50% for 9 hours because of unexpected electrical demand. | |
| April 26<br>00 : 28 | In continuing the power rundown, the operator made an error which caused the power to drop to 1%, amost shutting the reactor off. | This caused the core to fill with water & allowed xenon to build up, making it impossible to reach the planned test power. |
| 01 : 00<br>01 : 20 | The operator managed to raise power to 7%. He attempted to control the reactor manually, causing fluctuations in flow and temperature | The RBMK design is unstable with the core filled with water, i.e., small changes in flow or temperature can cause large power changes, and the capability of the emergency shutdown is badly weakened. |
| 01 : 20 | The operator blocked automatic reactor shutdown first on low water level, then on the loss of both turbines. | He was afraid that a shutdown abort the test. Repeat tests were planned, if necessary and he wanted to keep the reactor running to do these also. |
| 01 : 23 | The operator tripped the remaining turbine to start the test. | |
| 01 : 23 : 40 | Power began to rise | The reduction in flow as the voltage dropped cased a gradual increase in boiling leading to a power rise. |
| | The operator pushed the manual shutdown button. | Because of the shutoff rod design, this had exactly the opposite effect of what was expected. The power increased rapidly instead of dropping. |
| 01 : 23 : 44 | The reactor power reached about 100 times full power, fuel disintegrated, and excess steam pressure broke the pressure tubes. | The pressure in the reactor core blew the top shield off and broke all the remaining pressure tubes. |

The accident really began 24 hours earlier, since the mistakes made then slowly set the scene that culminated in the explosion on April 26.

Table (2) shows a summary of the accident sequance.

## THE DYNAMIC ANALYSIS

Consider the point kinetics equations,

$$\frac{dP(t)}{dt} = \frac{\rho(t)-\beta}{\Lambda} P(t) + \sum_{i=1}^{6} \lambda_i C_i(t), \quad (1)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} P(t) - \lambda_i C_i(t), \ i = 1,2,...,6 \qquad (2)$$

where $P(t)$ ≡ reactor power at time t,
$\rho(t)$ ≡ reactivity at time t,
$\Lambda$ ≡ prompt neutron generation time,
$C_i(t)$ ≡ Concentration of the delayed neutron precursor of group i,
$\lambda_i$ ≡ decay constant of the delayed neutron precursor of group i,
$\beta_i$ ≡ delayed neutron fraction of group i,
and $\sum^{i}_{\beta_i}$ = total fraction of the delayed neutrons.

Equations (1) and (2) give the reactor power P(t) in terms of the time-dependent reactivity $\rho(t)$. The reactivity $\rho(t)$ that drives the transients is the net effect of all contributions arising from several mechanisms and can be written as:

$$\rho(t) = \rho_i(t) + \rho_{fb}(t) + \rho_c(t) + \rho_{Sd}(t), \qquad (3)$$

where:

$\rho_i(t)$ reactivity caused by the initiating event,
$\rho_{fb}(t)$ reactivity from thermal-hydraulic feedback,
$\rho_c(t)$ reactivity from the reactor power control system,
and $\rho_{sd}(t)$ shutdown or trip reactivity.

The reactivity insertion caused by the initiating event may be often represented as an explicit function of time.

As shown from accident scenario of the Chernobyl reactor, the core was heavily xenon poisoned at the time of the accident. The control rods were at the upper edge of the reactor. Because of the xenon the axial shape of the thermal neutron flux was unusual, with high flux at the top and bottom and a depression in the center. If the reactor power had been constant or changing slowly, most of the steam would have been at the top of the channels because steam builds up axially toward the top. In that case, the greatest flux increase during the excursion would have been at the top because the water is displaced by steam, which capture fewer neutrons, and many fission neutrons can leak to the axial graphite moderator and be thermalized. However, the control rods are also in this zone, and being in a high thermal neutron flux area, would have been very effective. So the flux increase probably occured near the bottom of the core where there was nothing to stop it.

Then, we can consider fast superprompt-critical excursion occurred at the Chernobyl reactor (unit 4). In this case delayed neutrons effect may be neglected and the kinetics equations (1) and (2) can be reduced to:

$$\frac{dP(t)}{dt} = \frac{\rho(t)-\beta}{\Lambda} P(t), \qquad (4)$$

where $\rho_o$ = total reactivity causing the excursion. The solution of Eq. (4) is:

$$P(t) = P_o e^{t/T} \qquad (5)$$

where T reactor period (time constant)

$$= \frac{\Lambda}{\rho_o v \beta} \qquad (6)$$

Eq. (5) describes the power change of the Chernobyl reactor during the accident initiation (t > 0). As shown from this equation the power increases exponentially with time.

## RESULTS AND DISCUSSIONS

The void coefficient [5] at Chernobyl reactor was positive (0.03) and constitutes the major contributer in $\rho_o$. If a rapid void increase of 50% is assumed, this yields about 1.5% reactivity increase. The value of $\rho$ 0.5% for U-235, and $10^{-3}$ second. Using Equations (6) and (5) we get,

$$T = \frac{10^{-3}}{10^{-2}} = 0.1 \text{ Second.}$$

Within this period the power increases 2.7 - fold in 0.1 second. Table (3) presents the power variation during the first second from accident initiation.

**Table 3.** Power variation during the accident initiation.

| Time, Second | $P/P_o$ |
|---|---|
| 0.1 | 2.718 |
| 0.2 | 7.39 |
| 0.3 | 20.10 |
| 0.4 | 54.60 |
| 0.5 | 148.41 |
| 0.6 | 403.43 |
| 0.7 | 1096.00 |
| 0.8 | 2980.00 |
| 0.9 | 8103.00 |
| 1.0 | 22023.00 |

From Table (3), we notice that, within one second, the power increased to about 2200 times full power which destroyed the reactor. This fast change in power put a sudden burst of heat into the uranium fuel, and it broke up into little pieces. The heat from these pieces caused a rapid boiling of the cooling water and broke all the pressure tubes. Also, the power surge destroyed the top of the reactor and the building above it.

## CONCLUSIONS AND LEARNED LESSONS

The dynamic analysis of the Chernobyl accident is developed on the basis of the accident sequence. The power variation during the accident is analyzed and calculated. From this analysis we conclude that:

1. The reactor containment is a powerful safety feature to confine the radioactive materials in the case of accidents.
2. Human reliability can be greatly improved by intensive operator training programs and clear operation procedures in emergencies.
3. The reactor must be provided by several interlocks that prevent to operator to insert dangerous positive reactivity.
4. The design of emergency shutdown systems must be revised to be more capable to overcome all sources of power increase.
5. Probabilistic safety assessment studies is very effective in identifying weak points in plant design and operations. It can help to prevent or mitigate future reactor accidents.

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