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NUCLEAR SAFETY IN QUESTION
ANSWER THROUGH PROJECT CONCEPT OF NUCLEAR POWER STATION SAFETY

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ABSTRACT

This paper briefly describes the environmental impacts of nuclear power. It focuses on the worst impact of this option - the leakage of radiation into the environment. To reduce this serious risk, the contribution presents a method of assessing and improving the safety of the plant on a static basis. This means that an increase in safety is based on a static analysis of a power plant system. The procedure is illustrated by a real nuclear power plant. This article does not deal with the dynamic aspect of the safe operation of nuclear power.

Keywords: Nuclear Safty, Structure of Organization, Information Transmission, Reliability

1 INTRODUCTION – MOTIVATION FOR THE PAPER AND OBJECTIVE

Two scares in quick succession occurred in the nuclear power plants of Forsmark in Sweden and Temelin in the Czech Republic approximately two years ago. Both incidents reminded Europeans of the Chernobyl disaster and the risks inherent in nuclear technology, one of Europe's chief energy sources. West European countries used to worry about the antiquity of East Europe's nuclear reactors, but since the fall of the iron curtain, power stations in the former Eastern bloc countries have been modernized and upgraded to EU safety standards - thanks to the know-how of Western contractors. In the 1990s the American company, Westinghouse, undertook the renovation of the Soviet-designed WER 100 pressurized water reactors at the Temelin plant in South Bohemia (Czech Republic), adding, for example, complete physical containment. That has not, however, prevented the Temelin plant from showing a "serious failing", and in the wake of the incident at the end of July of the same year at Sweden's Forsmark plant, the European nuclear safety debate is once again an issue. Probably it's no coincidence that two serious incidents at European nuclear power stations occurred on the same day. At Sweden's Forsmark power station, central safety systems failed. One expert referred to this as the most serious incident since Chernobyl. This effectively silences claims that a serious accident couldn't occur at a Western nuclear power station. At almost the same time several thousand liters of radioactive water leaked from the Czech Republic's Temelin power station, which is just a few dozen kilometers away from the Austrian border. Only shortly beforehand a reactor block had been shut down because of a leaking oil pipe. Both incidents are a signal and will reignite the discussion about the safety using nuclear power in Europe. This is a good thing, because it was just looking very much like the use of this source of energy would increase on the continent.

The objective of this paper is to introduce the principle of a new methodology for static reliability measurement of a large system which would have a serious environmental impact in the case of a defect.

2 LITERATURE REVIEW & METHODS

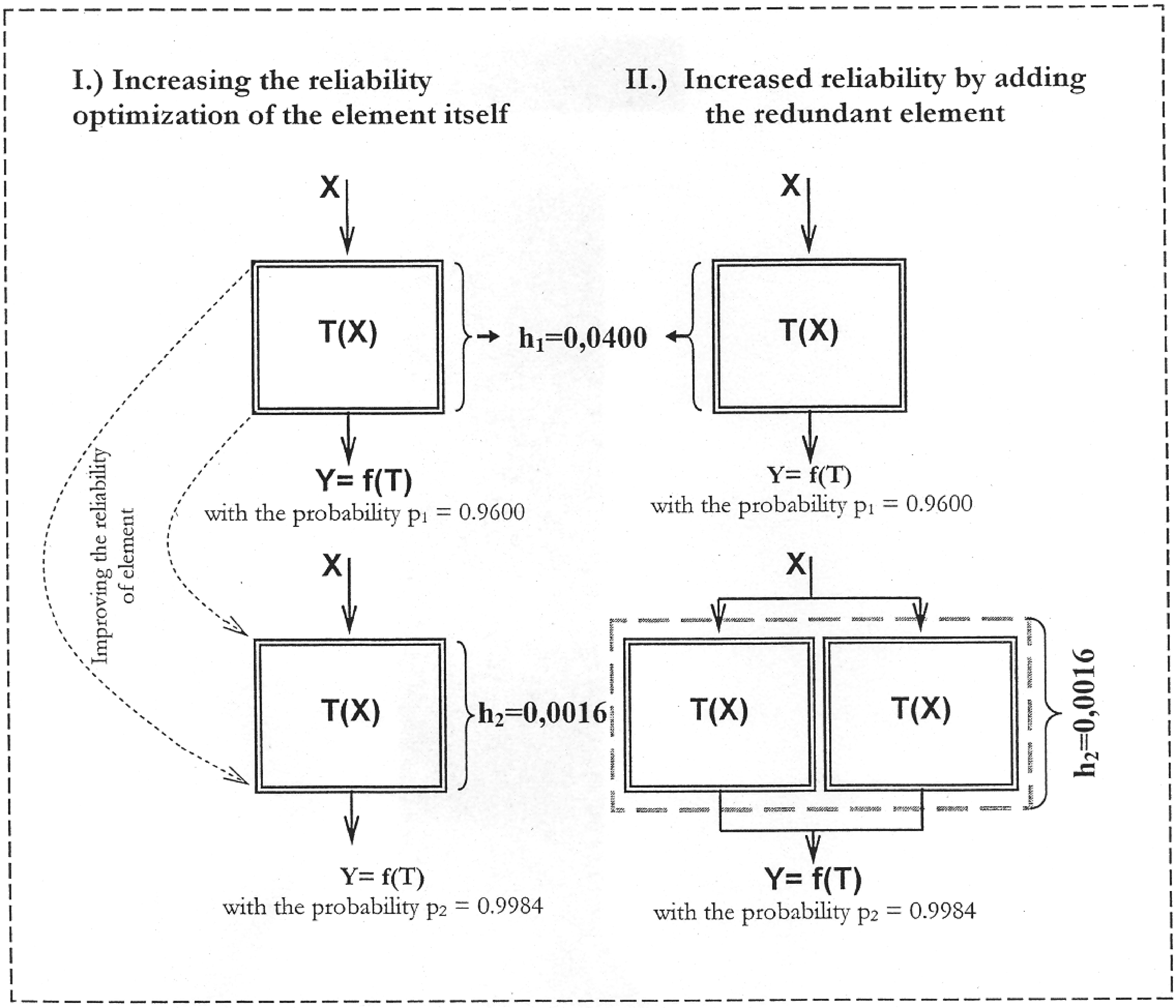
In contemporary management, in whatever system is employed, we must consider the possibility that the required output may not always be reliably obtained (Hron, 2007). In general, we can formalize the uncertainty of the output system to be like the probability of a failure of the system element during its activity time. If we know the probability of any component's failure-free working during its lifetime (p), then we can determine a value of the component's unreliability (h), by way of simple subtraction from the expected reliability: $h=1-p$. For example the management of a vehicle servicing organization can statistically calculate that a modern, best selling car does not need to be repaired during the duration of the guarantee in 96 of 100 cases. The reliability of the car during the guarantee period is therefore $p=0.96$, and its measure of unreliability is then $h=0,04$. This data about the unreliability of a system (here about manufactured product) is very valuable for a manager. The date about unreliability allows the manager to identify what additional costs must be added to production costs for the purposes of calculating profit.

Shown diagrammatically, it is possible to represent a methodology for reducing unreliability in the following way:

I. Couplers' safety optimalization,

II. Adding duplicate or standby components.

Figure 3.1 Two methods of increasing system reliability from the structure point of view



Now, based on the schematic shown in figure 3.1 we will show how to determine the reliability of the resulting behavior of two parallel connected elements. Reliability theory is based on the application of probability theory to systems theory.

Let us make an experiment. We are playing with the same two dice cubes, which are identical in every way, it can therefore be assumed that the probability of a 1 showing is the same as the value of any other number, 2 to 6. Imagine that each element of the game cube is a system. If the failure of an element is a random variable, then it cannot it removed, and it is only possible to attempt to predict the likelihood of failure. The malfunctioning component will represent the value of number "six" on the dice. The question is, what is the probability that both dice in one throw show sixes? This reasoning is similar to considering the possibility of both main and standby channels failing simultaneously.

The probability that any one dice falls as a six is equal to $p_1 = \frac{1}{6}$, however the probability that both fall six, is equal to the resulting probability:

$$p(p_1 \, a \, p_2) = p_1 \;\; from \;\; p_2 = \frac{1}{6} \;\; from \;\; \frac{1}{6} = \frac{1}{6} \times \frac{1}{6} = \frac{1}{36}$$

In a similar way we can consider the unreliability of two elements connected in parallel, where one appears as a redundant element. Let us consider the general case, where the elements do not have the same uncertainty:

(3.1) $$h = h_1 \times h_2$$

Where h_1 is the unreliability of first element and h_2 is the unreliability of second element.

If we have ***n-1*** redundant elements, (where ***n*** is the total number of elements connected in parallel), the resulting uncertainty would be obtained by multiplying together the unreliability associated with each interconnected parallel element:

(3.2) $$\boxed{h = h_1 \times h_2 \times \quad \dots \quad \times h_n = \prod_{i=1}^{n} h_i}$$

For the system where the unreliability of each element is the same value, i.e. $h_1 = h_2 = \dots = h_n = const$, the formula (5.2) becomes:

(3.3) $$h = h_i^{\,n};$$

Where **n** is the number of parallel elements and **i** is any element: $i \in \{1,2,\dots,n\}$

If we use formula (3.2) needed to determine the reliability of a system composed entirely of parallel elements, we can identify it as a complement to the unreliability of the resulting h, namely:

(3.4) $$\boxed{p = 1 - \prod_{i=1}^{n} h_i;}$$

Indicating partial unreliability hi-shaped reliability (h = 1 - p) and by (3.4), we obtain the formula to calculate the overall reliability of the system composed entirely of parallel connected elements:

(3.5) $$\boxed{p=1-\prod_{i=1}^{n}(1-p_i)}$$

In an organizational system, generally there are not only the redundant elements. Some elements of the organizational system are connected in series. For example, to transmit the information needed to implement the strategic plan for the operational processes is is necessary to inform the strategic organizational's tactical unit and the then operational unit. In terms of the resulting transfer of information, there is a need to overcome the interference of three organizational elements.

The resulting reliability of information transmission system, we obtain by multiplying each of the trustworthiness factors of each of the corresponding series-connected elements (usually located in a different level of management).

(3.6) $$\boxed{p = p_1 \times p_2 \times \quad \dots \quad \times p_n = \prod_{i=1}^{n} p_i}$$

To determine how information is manipulated by the content of the resulting behavior measured in the operational organization, we will spread the structure into three series-connected blocks, with each block represents one level of management. In terms of information, the final link reliability of each block is based on the formula (3.6), the product of the reliability of individual blocks. Now, we should determine the reliabilities of what we can calculate in these blocks. In the first block there is only one organizational unit; the reliability of this block is equal to the reliability of *ps = 0.95*. In the second and third blocks are more functional units, therefore their reliability must be firstly determined according to formula (3.5).

Reliablity of the first block: $p_1 = p_s = 0{,}95$

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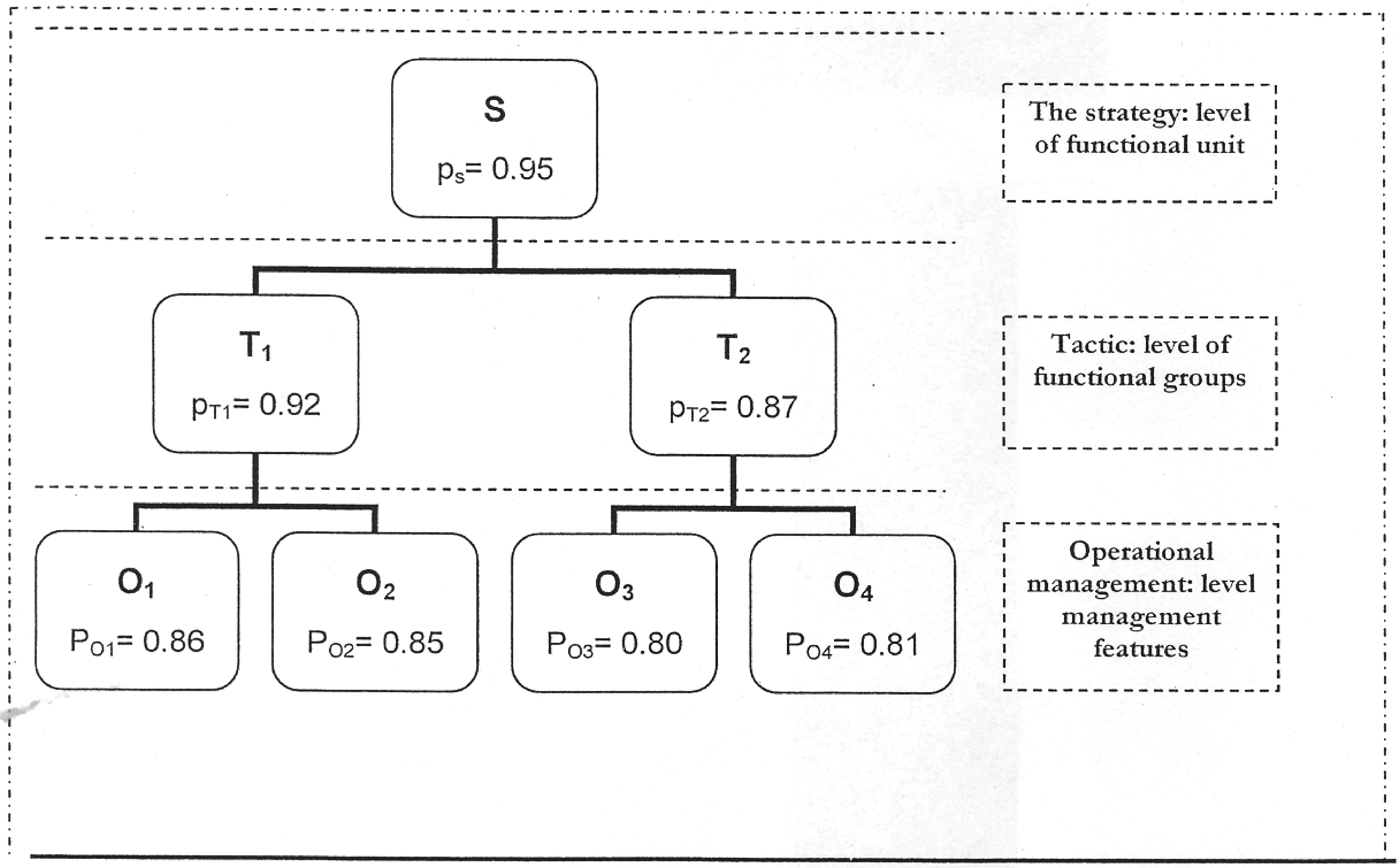
Reliablity of the second block: $p_2 = 1-\prod_{i=1}^{2}(1-p_{T_i}) = 1-[(1-0{,}92)\times(1-0{,}87)] = 0.9896$

Reliablity of the third block: $p_3 = 1-\prod_{i=1}^{4}(1-p_{O_i}) = 1-[(1-0{,}86)\times(1-0{,}85)\times(1-0{,}80)\times(1-0{,}81)] = 0.864522$

Figure 3.2: Functional structure of the organization, with three levels of management and seven organizational units



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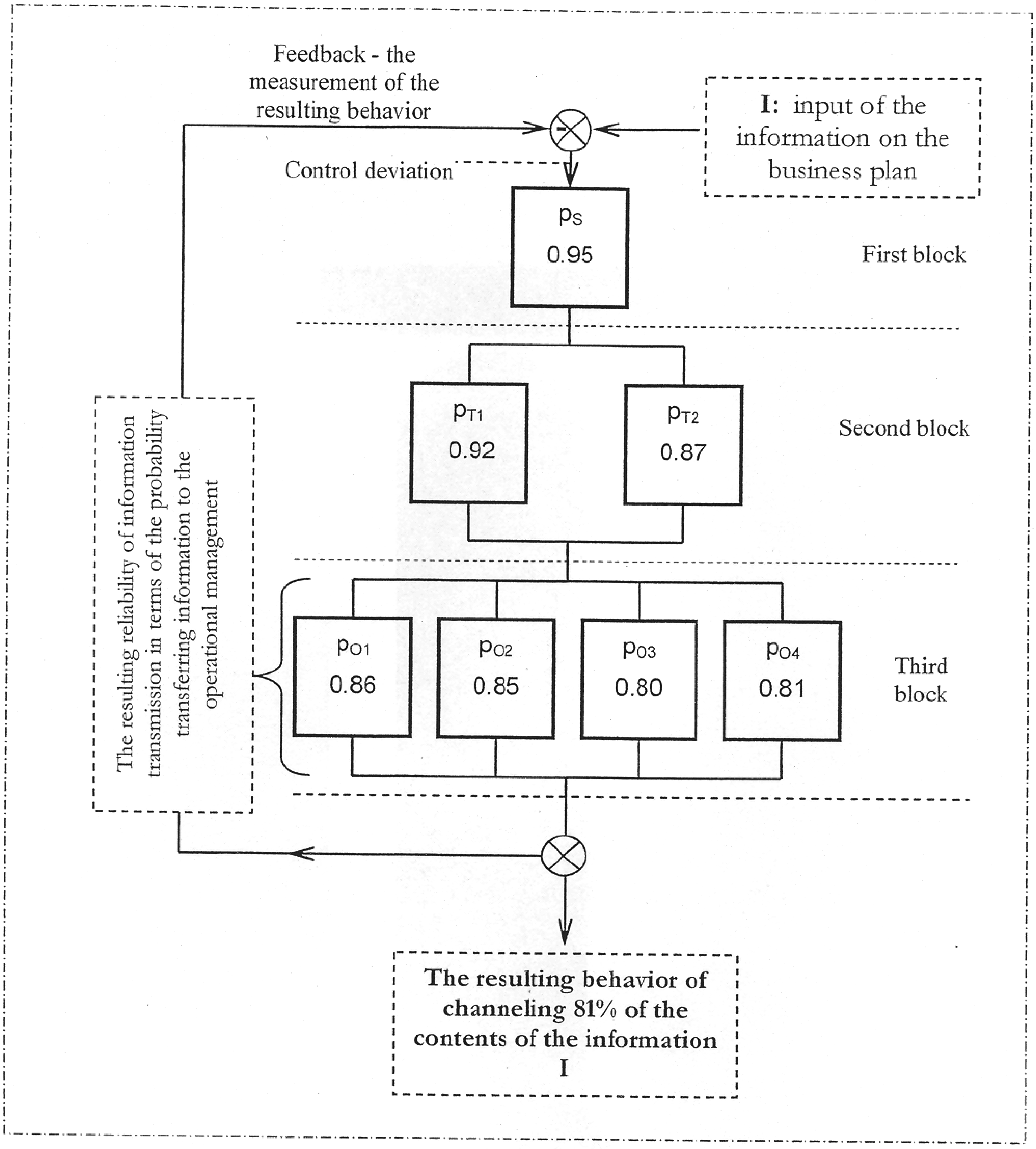
Reliablity of the third block: $p_3 = 1 - \prod_{i=1}^{4}(1 - p_{O_i}) = 1 - [(1-0{,}86)\times(1-0{,}85)\times(1-0{,}80)\times(1-0{,}81)] = 0.864522$

The resulting reliability of information transmission in terms of probability transferring information to operative:

Figure 3.3 Diagram of the information transmission between organizational units



The reliability of the entire organizational system is then, by equation (3.6), the product of the reliability of the series-related blocks:

$$p = \prod_{i=1}^{3} p_i = p_1 \times p_2 \times p_3 = 0{,}95 \times 0{,}9896 \times 0{,}864522 = 0{,}8128 \cong 81\% \; of \; \mathrm{I}$$

Based on this progress, we can create a formula for the general result of the determination of any system composed of interconnected elements in both parallel and serial links. There is a need to know only the reliability of the individual elements:

$$\boxed{p = \prod_{j=1}^{n}\left[1-\prod_{i=1}^{m}(1-p_{ij})\right]}\;; \tag{3.7}$$

where **m** is a variable number of elements connected in parallel (in our example it is the number of elements in 3 blocks), and **n** is the number of elements connected in series (in our example the number of blocks).

3 THE RESULTS OF THE PAPER

The number of standby units must continue to respect the requirement that the implementation and maintenance costs demand minimum resources, namely to achieve the result of what was the cheapest. It is based on a combination of two strategies mentioned above - from optimization of the reliability of the serial link, as well as the involvement of additional parallel links generating standby elements. Usually, according to cost criteria, we prefer to optimize the reliability of the elements. If, however, we require that the system is extremely reliable, for example, because of threats to the safety of staff or potential of a large loss (not only a financial matter, but also large environmental impacts), we usually must go through a combination of both basic strategies of increasing reliability.

The combination of using both of these strategies is typical for a complex management system. A complex system is, characterized by a large number of functional elements, among which there are many links. The characteristics of a large system lie not just in a large number of its constituting elements and the complexity of their ties, but in particular those that unite in single complex, heterogeneous subsystems whose individual behavior is described by different rules.

Under the initial vision system (S) referred to in the literature (Hron, 2007), where the system is defined as a set: $S=\{A,R\}$ - in which (A) is the set of elements and (R) is the set of links, a large system can be characterized as a system:

- ☒ **with a large number of heterogeneous elements interconnected complex linkages**, the individual functions interact so that the change in the function of one element is reflected in a change in behavior of the whole system in its surroundings;

- ☒ **with a homogenous organization,** expressed its single operational structure to achieve certain objectives of the system, regardless of the quantity and variety of its elements. In practice, this means that the strategic objective of the system is above the individual objectives of different subsystems (e.g. organizational, environmental, managerial, economic, technical, etc.);

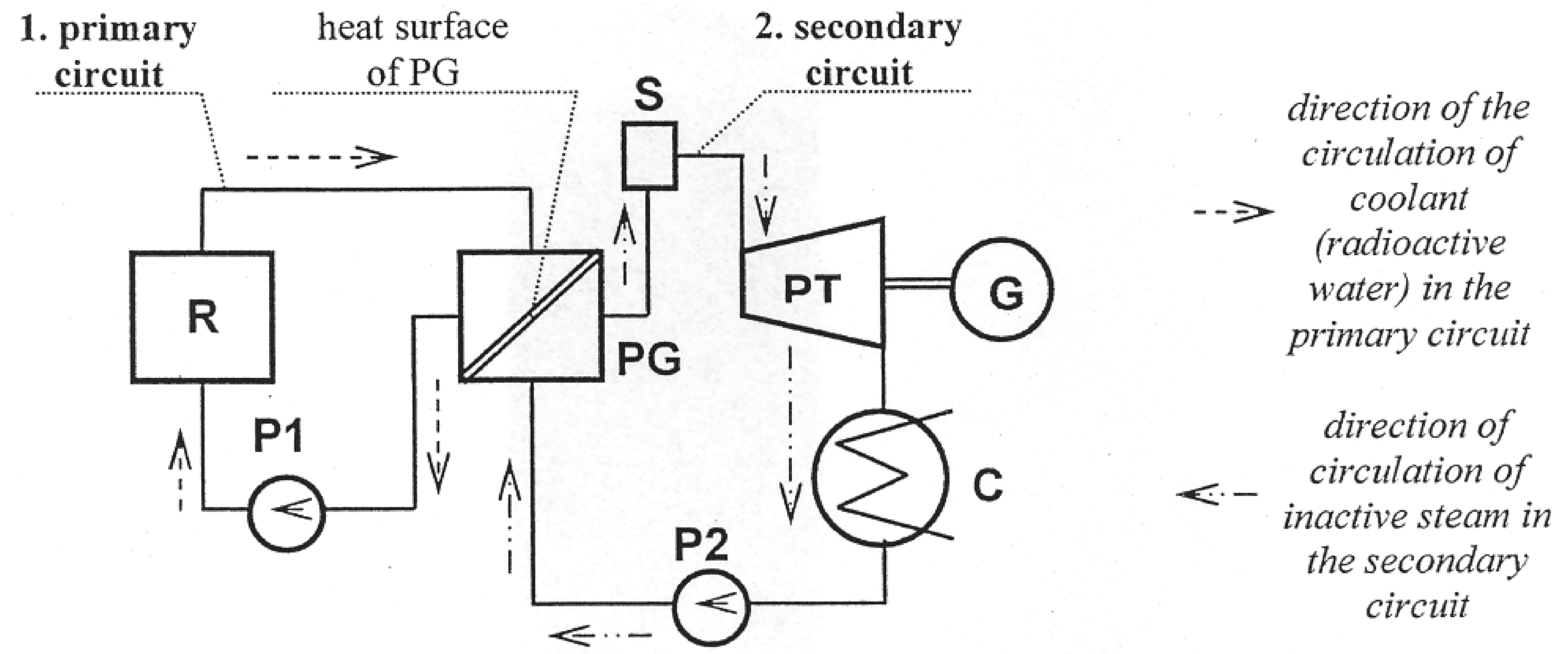
- ☒ **with variable (adaptive) functions** resulting from the need to secure more operating modes, which cannot be secured only by changing the functions of the individual elements, but only by adequate changes in its internal organization in response to changes in its substantial exposure to the surroundings.

Given the vastness of the system, the only effective management system is based on the hierarchical structure of management functions and the resulting ***hierarchical structure*** of organizational units. The management system is the concept of being flexible enough to also be able to respond to the input of an accidental operation surrounding the organization. Due in part in the life of the unpredictability of external influences **is not usually possible to build a secure operating organization which considers only cost criteria. To determine the required level of reliability throughout the organization, it is necessary to consider the wider social impact of the criteria (for example, the criteria of environmental impact under the concept of Green Management). The procedure of analysis of a large projection system can be shown in the following real case study.**

Identifying the level of large system to minimize the negative impact on the environment – Temelin nuclear power plant

The current nuclear power plant is an organizational system - industrial equipment, which is using nuclear fission to produce energy in the form of heat, which is gradually transformed to a desired final form - electricity. The block diagram of Temelin nuclear power plant (in the first distinguishing level) is shown in figure 4.1.

Figure 4.1 Diagram of functional units block of power plant, consisting of two cycles



The units of the primary circuit are: **R** - nuclear reactor, **PG** - steam generator, **P1** - pump (in the primary circuit).

The secondary circuit units are: **PG** - steam generator, **S** - steam separator, **PT** - steam turbine, **G** - generator of electricity, **C** - condenser, **P2** - pump (in the secondary circuit).

The principle of nuclear power generation is schematically described in Figure 4.1. In the primary circuit of a nuclear power plant (with a pressurized water reactor) a main circulation pump transports pressurized water from the ***steam generator*** to the reactor. This leads to the cooling of the reactor - by circulating water, which then heated steam in the ***steam generator***[1]. Steam heated in the steam generator is then conveyed to the separator, where the water is separated from the preheated steam before entering

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[1] Steam generator is a device composed of a significant number of small diameter tubes (from 11 mm to 21 mm) and a small wall thickness (1.0 to 1.5 mm) - a small wall thickness is beneficial for low resistance to heat management. Inside these tubes flow pressure water heated from the primary circuit of the reactor, while the area around the steam pipes is the secondary circuit, which is from the hot surface of, the tube is heated.

into the ***steam turbine***[2]. After its expansion in the turbine, steam is also conveyed to the condenser. Hence the condensate pump transports, via low ***regenerative heaters***[3]**,** to gas-realized equipment, located in the supply tank (not included in figure 4.1.), which supplies the water degassing pump transported via high pressure ***regenerative heaters*** back into the steam generator.

The organizational system is characteristic of a large system:

It consists of a large number of disparate elements, whose individual behavior is described by laws with different characteristics - for example:

- Laws on which the management of a fission chain reaction in a nuclear reactor is based;
- Patterns of Fluid Mechanics and Thermo-Mechanics concerning cooling the reactor and steam flow through a steam turbine;
- Law of electromechanical conversion of the rotary mechanical energy to electric energy.

Now, let us try to determine the reliability of the whole nuclear power plant in relation to security against leakage of radioactivity into the environment. Leakage of radioactivity is only possible from the primary circuit electricity block, because the circuit in the secondary circulation medium (water and steam) is not radioactive. The aim is to determine the output of the system - in this case the final value of the static point of view. To achieve this objective, we need to increase the detail of an investigation of the individual functional units in the primary circuit (nuclear reactor, steam generator, pumps). We will therefore investigate these elements in the second distinguish level (i.e.: sub-components). For these components it is possible to ascertain the reliability from the manufacturer's specification sheets. To determine the overall reliability of the primary circuit it is also necessary to consider the reliability of links between the elements. Here, the link represents a pipeline through the coolant (water) which leads away thermal power produced by the fission chain reaction in the reactor. Because the pressured water is radioactive in the pipes of the primary circuit, a leak in a pipe would lead to a leak radioactivity into the environment.

The reliability of the block of nuclear power plant is determined according to the three functions:

1. *The reliability of the nuclear reactor control block;*
2. *the reliability of the nuclear reactor cooling block;*
3. *the reliability of the primary circuit proofing (circulation pipes).*

Now, we will sequentially determine the reliability of these individual blocks.

Ad 1. The reliability of the nuclear reactor control block

A **nuclear reactor** is a device in which nuclear chain reactions are initiated, controlled, and sustained at a steady rate, as opposed to a nuclear bomb, in which a chain reaction occurs in a fraction of a second and is uncontrolled causing an explosion (Bodansky, 1996; Racek, 2004).

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[2] Steam turbine is a device- heat engine in which the amended energy working substance (overture high vapor pressure) to mechanical energy, which will as a revolving round revolution. This rotational energy is then transferred using a generator for electricity with the required electricity networks.

[3] Regenerative heater is in addition to moisture separator other devices to reduce the water content in the circulation of steam and this contributes to more efficient steam turbines - for maximum thermal efficiency of power needs to drive a steam turbine overheating pair to maximize the temperature and pressure.

A nuclear reactor can be described as a group consisting of:

- Fuel Cells: containing fissile material, which leads to fission of heavy nuclei and the release of thermal energy;
- Reactor control system, which allows the operation of the reactor at constant power, change the modes of operation, running and shutdown of the reactor;
- Heat removal system, which ensures the safe removal of heat from the core, and thus prevents heat damage to the reactor;
- Reflector (mirror neutron), which reflects back neutrons escaped from the system and helps to compensate for spatial distribution of heat;
- Shielding for the reactor, which minimizes the acceptable level of penetration of radiation into the environment reactor.

The control block of the reactor is based on absorbing excess neutrons compensation (by control rods of boron carbide). In addition to these bars, there are in the regulatory system, instant response premium bars, which fall into the reactor to stop the reaction in the case of a failure. One example is the failure, when the cooling water exceeds its boiling point (at 100 atmospheres it is 309 ^{0}C), damaging the fuel rods. Therefore, continuous monitoring of the temperature of the water ensures the bar automatically stops the operation of the reactor, if the water temperature exceeds a predetermined limit. These bars are also managing to hasten a situation where it is not possible to successfully manage the transmitter power reactor through the control rods.

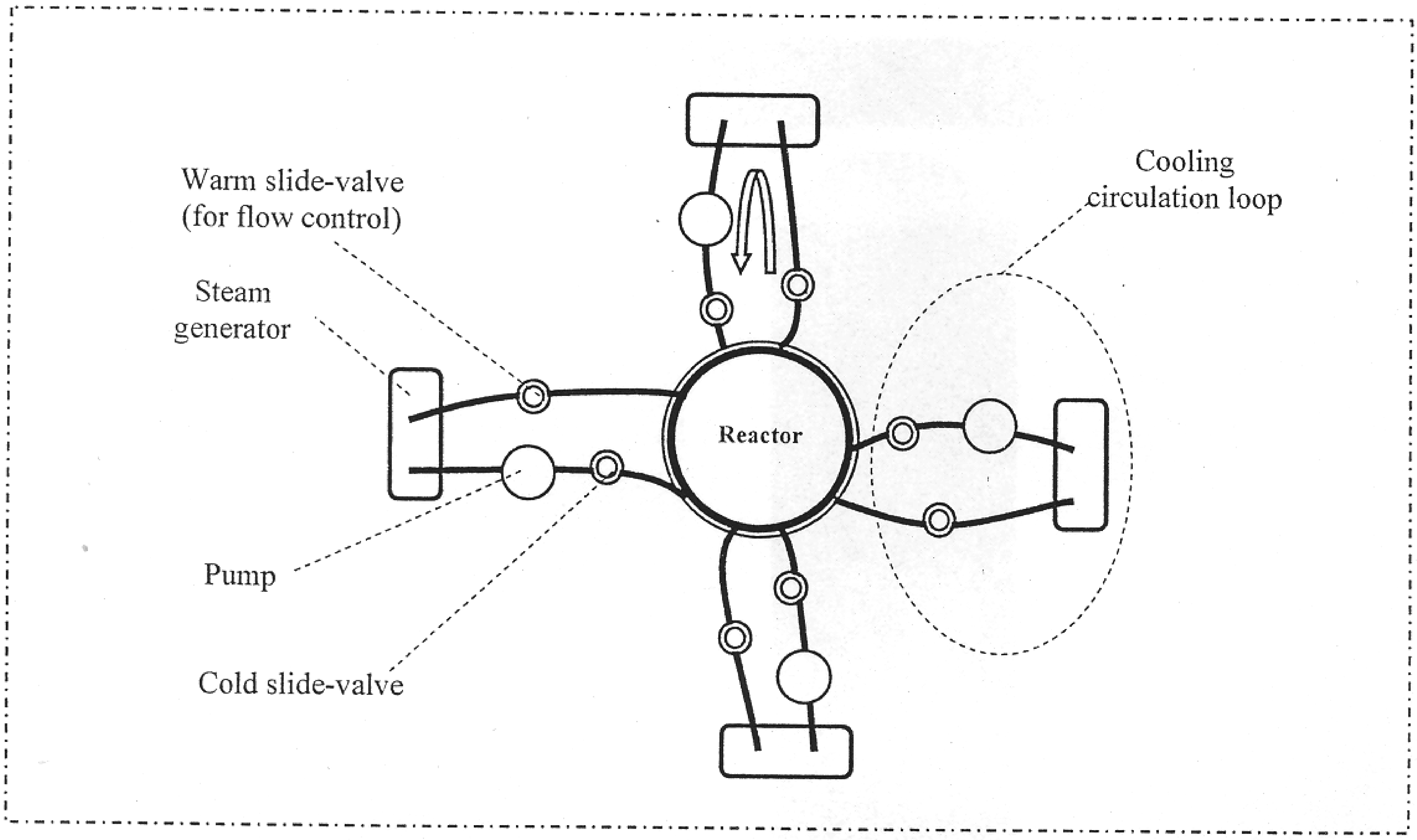
Let us assume that the reliability of the control rod is p_{11} = 0.99998 during their service life. Furthermore, that the reliability of the safety bars p_{12} = 0.99995 during its service life.

$$p_1 = 1 - \prod_{i=1}^{2} h_i = 1 - \left[(1 - 0{,}99998) \times (1 - 0{,}99995)\right] = 0{,}999999999$$

Ad 2. Reliability of nuclear reactor cooling block

A cooled reactor has two complementary functions. Firstly, it is to drain thermal energy released by fission reaction in the reactor, to avoid overheating the reactor casing and its destruction (water acts as a moderator - slowing fast neutrons, and thus helps to regulate the reaction). And secondly, the heated water is used to heat steam in the secondary circuit, which is then used to drive the steam turbines. Cooling the reactor is achieved by a series of circulation loops, connecting with each reactor steam generators (see Figure 4.2). Cold branches flow from the steam generator cooling water, which is transported back to the reactor via the circulation pump. Temelin nuclear power plant is (as shown in figure 4.2) attached to the four reactor coolant loops.

Figure 4.2 Four circular cooling loops of the Temelin's reactor



Let us assume that the reliability of the circulation pump is p_{21} = 0.9970 during its service life . Furthermore, that the reliability of the cold and warm damper branches are $p_{22} = p_{23}$ = 0.9990 during their service life. In terms of operational security, it is sufficient if at least one cooling loop should remain in operation.

The resulting reliability of cooling the reactor is given by the parallel and series-connected elements.

$$(4.1)\quad p = 1 - \prod_{i=1}^{4}\left(1 - \prod_{j=1}^{3} p_{ij}\right) = 1 - (1 - 0{,}997 \cdot 0{,}999 \cdot 0{,}999)^4 = 0{,}9999999990$$

Ad 3. The reliability of the primary circuit proofing (circulation pipes)

From the primary circuit proofing point of view, it is necessary to ensure that not only do the functionality of the key components of control of this circuit operate as expected (it was resolved in paragraphs 1 and 2), but also impermeability (tightness) of the individual components of the primary circuit and the tightness of the pipe itself the primary pipeline. **Reliability in the form of leakage is measurable and thus a controllable variable.** It is defined by unit $\left[Pa \cdot dm^3 \cdot s^{-1}\right]$, that is, as the closeness of the vessel on its internal volume of one liter $\left(dm^3\right)$, which increase pressure on the value of one of one Pascal (Pa) state vacuum for one second of time (s). The maximum permissible level of leakage is given by the value $10^{-4}\, Pa \cdot dm^3 \cdot s^{-1}$. The individual elements of the primary circuit in not exceeding the maximum allowable leakage are shown in Table 4.1. The resulting reliability is the product of the reliability of individual elements of the primary circuit:

$$p_3 = \prod_{i=1}^{11} p_{3i} = 0{,}999998 \times 0{,}999970 \times 0{,}999950 \times 0{,}999920 \times 0{,}999940 \times 0{,}999920 \times 0{,}999992 \cdot$$

$$\times 0{,}999960 \times 0{,}999940 \times 0{,}999965 \times 0{,}999956 = 0{,}999511$$

Table 4.1. The reliability of the primary circuit in the field of non-exceeding the authorized leakage limit.

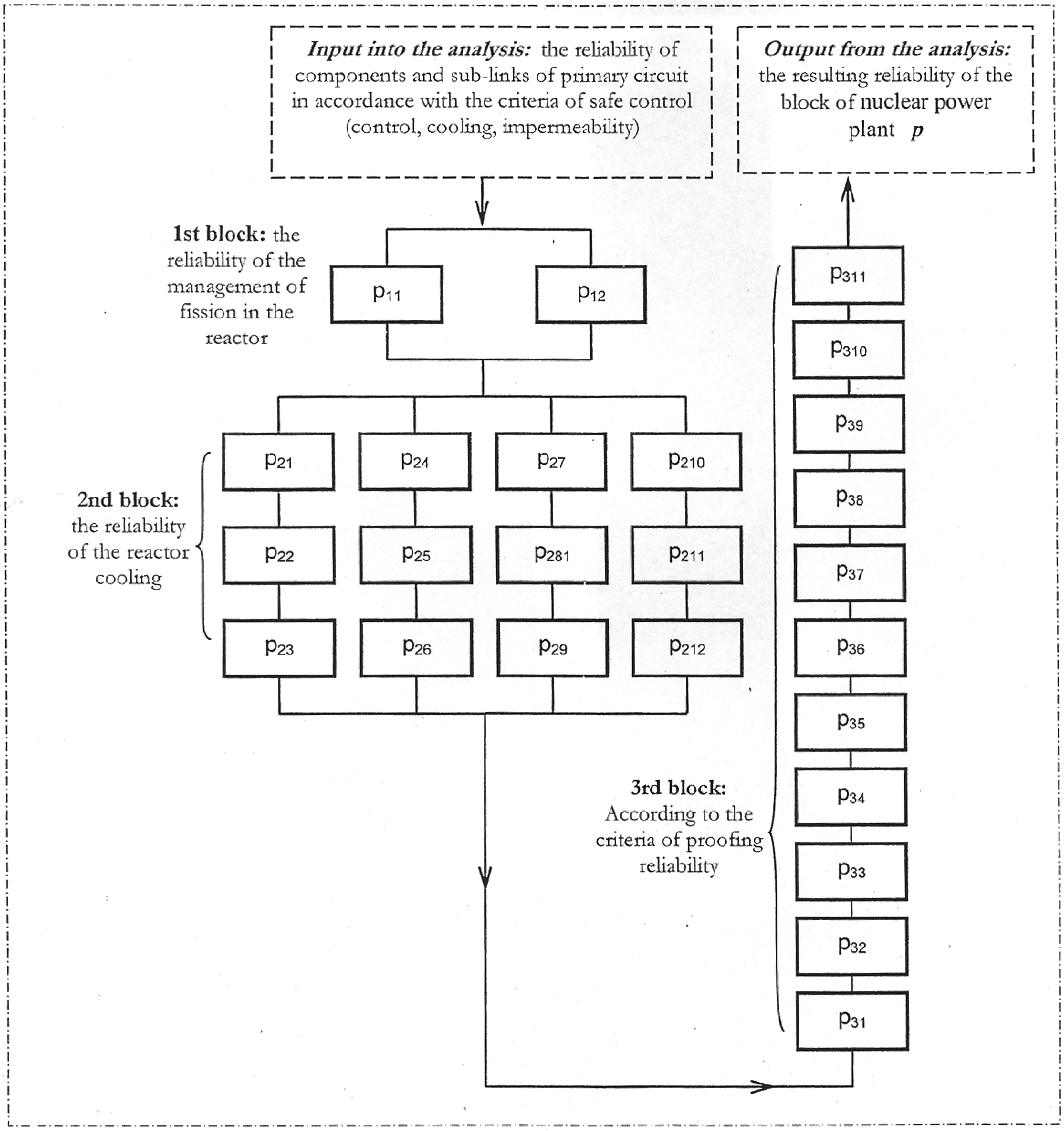
Order of component	***Title of component***	***Reliability in the form of the probability of non-exceeding the maximum allowable leakage***
1	*Nuclear Reactor (in the form of a reduction of escaping radiation to an acceptable level*	$p_{31} = 0.999998$
2	*Primary circuit pipes (creating links between the different elements)*	$p_{32} = 0.999970$
3	*Volume Compensators*	$p_{33} = 0.999950$
4	*Active part of the steam generator*	$p_{34} = 0.999920$
5	*Two shut-off valves*	$p_{35} = 0.999970^{2} = 0.99994$
6	*Four circulation pumps (one in each loop cooling)*	$p_{36} = 0.999980^{4} = 0.99992$
7	*Eight slide-valves (two for one loop cooling)*	$p_{37} = 0.999999^{8} = 0.999992$
8	*Regeneration heater of cleaning system*	$p_{38} = 0.999960$
9	*After-cooler*	$p_{39} = 0.999940$
10	*Filter*	$p_{310} = 0.999965$
11	*Cleaning station*	$p_{311} = 0.999956$
	The resulting reliability according to proofing criterion: $p_3 = \prod_{i=1}^{11} p_{3i}$	$\boldsymbol{p_3 = 0.999511}$

Determination of the resulting nuclear power block

The resulting reliability of the entire nuclear power block is given by the product of the reliability of the reactor control (p_1), in the cooling reactor (p_2) and proofing of the primary circuit (p_3):

$$p = p_1 \times p_2 \times p_3 = 0{,}9999999 \times 0{,}9999999990 \times 0{,}99951 = 0{,}9995099$$

Figure 4.3 Diagram of the analysis of the resulting radiation leakage in the block of power plant



4 CONCLUSION

The most serious negative impact on the environment is a nuclear power plant accident (Cravens, 2007). This actually happened in the last 6 serious accidents in nuclear power plants. The worst nuclear accident was in Chernobyl. During an experiment, a reactor exploded. The result was that a radioactive cloud was blown by the wind from the former Soviet Union to Western Europe. Radiation resulting from this cloud was the worst environmental impact in recent times.

The second worst environmental impact is that of nuclear waste. Though the fuel is spent, it still emits a strong radioactivity, which is very dangerous, therefore the waste must be securely stored. The spent fuel has to be stored in special drums and under strict security conditions in deep underground storage. The problem is, exactly where to store it. Another reason is that the safe deposit of waste in the water solubility. The spent fuel must be kept in storage for a few thousand years. Spent fuel can also be processed in different ways to produce a new fuel, which modern (fast) reactors will have as a raw material. For these reactors there is almost no waste material to be saved. This waste is radioactive for a shorter time.

Third worst impact on the environment is water and air pollution. Nuclear Power consumes large quantities of water. Most of this water is evaporated into the air (this also causes an increase in the average air temperature in the vicinity of nuclear power plants). This will also concentrate the pollutants, which occur in water, which is recycled.

While there are negative impacts, nuclear power has great advantages. There is, for example, no smoke pollution released into the air from thermal power. Nuclear power plants take up a relatively small land area in proportion to the size of production, when compared to wind, solar and water (reservoirs flooding a large area) power.

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