International Journal for Quality Research 7(4) 595–604
ISSN 1800-6450

Dobrivoje Catic[1]
Milorad Bojic
Jasna Glisovic
Zorica Djordjevic
Nada Ratkovic

Article info:
Received 4 March 2013
Accepted 25 April 2013

UDC – 65.012.7

FAULT TREE ANALYSIS OF SOLAR CONCENTRATORS

Abstract: *In the introductory part, the history development is presented, and it points out the importance of using the Fault Tree Analysis - FTA method for analysis of the reliability and safety of technical systems. By analyzing a number of references related to the FTA method, the FTA methodology is established, and explanation of some steps by this method is given in this paper. As an example of the practical application of methods, the failure of the solar concentrators is analyzed.For the failure analysis of the considered device, it is necessary to know the structure, functioning, working conditions and all factors that have a greater or less influence on its reliability. Along with an explanation of certain parts of the fault tree, the estimation of the significance of certain events is done, and it is considered to be able to eliminate causes of failure or to minimize the consequences of failure.*

Keywords: *Fault Tree Analysis, Methodology, Solar Concentrator, Qualitative Analysis*

1. Introduction

The Fault Tree Analysis - FTA is one of the basic and the most used methods for analysis of the technical system's reliability and safety. FTA is a deductive method, where at first, the so-called top event, which at the technical systems represents a failure, and then the possible causes of this failure inside the system are analyzed. Basis of the fault tree represents a transformation of physical systems to the structural logic diagrams.

The FTA method was invented and developed in 1961 by H. A. Watson at Bell Telephone Laboratories in connection with a US Air Force contract to safety study of the Minuteman Launch Control System (Watson, 1961). After the initial work at Bell Telephone Laboratories, development of the fault tree continued at the Boeing Company, where the technique was applied to manned aircraft and simulation techniques were used extensively. In 1965, D. F. Haasl of the Boeing Company further developed the technique of fault tree construction and its application to a wide variety of industrial safety and reliability problems (Haasl, 1965). Boeing in 1966 was the first commercial company that started to use the FTA for the development of commercial aircrafts (Hixenbaugh, 1968). In the seventies, the method was used in particular in the area of nuclear power techniques. From its beginnings until today, the FTA was used for failure analysis of different technical systems. This method is especially convenient for the reliability and safety analysis of the systems whose failures might cause catastrophic consequences for mankind and environment.

[1]Corresponding author: Dobrivoje Catic
email: caticd@kg.ac.rs

The FTA gives the best results in new products designing, because of the fact that by using this method the potential failure causes are eliminated or reduced to a minimum, at the very beginning of the analysis. This method can also be used in exploitation period for the maintenance needs, for diagnostics of the failure cause, for getting feedback-information about possible modifications of the system and its parts, etc.

Construction and analysis of a fault tree is best performed as a product development team activity. Even though an individual may attempt the FTA, the trees that are developed by a team are generally more fully defined and complete. The reason for this is that a much broader sphere of information is presented and considered by a team.

Hybrid solar receivers enable simultaneously generating both heat and electricity. In order to increase the energy efficiency of solar receivers, reflective surfaces are used that allow the concentration of solar energy (Strebkov*et al.*, 2007).

Practical application of the FTA in the process of product development is illustrated by the FTA of a hybrid solar concentrator, which was developed within the research project at the Faculty of Engineering University of Kragujevac(Stationary solar hybrid concentrator for generation of electricity and heat, 2007; Bojic, 2007; Bojic, 2008).

2. Methodology of the fault tree analysis

The FTA methodology is described in several industry and government standards, including NRC NUREG–0492 (Roberts *et al.*, 1981) for the nuclear power industry, an aerospace-oriented revision to NUREG–0492 for use by NASA (Vesely, 2002), SAE ARP4761 for civil aerospace, MIL–HDBK–338 for military systems (Faulty tree analysis, Electronic Reliability Design Handbook, 1998) for military systems.Many different approaches can be used to model the FTA. Based on the analysis of implementation procedures of the FTA described in the above standards and references starting from (Hixenbaugh, 1968), over (Dhillon, 1985), to modern literature references from the subject area (Ericson, 2005; Yang, 2007), the FTA methodology is comprises the following steps:

1) Define the system of interest and any assumptions to be used in the analysis.
2) Establish the boundaries and objectives of the system. If it is necessary to simplify the scope of the analysis, develop a simple block diagram of the system, showing input, output and interfaces.
3) Define the top event of the fault tree. Depending on the analyzed system, it can be general, in the form of a system failure, or a specific case involving only a few failures of the system or its components. Careful choice of the top event is very important for the success of the analysis.
4) Systematic collecting the system data (documentation, calculations, catalogues, service instructions, users' complaints etc.) and their analysis. It is required from an analyst to study the system carefully also considering the functioning and failure occurrences, before he start constructing the fault tree.
5) Construct the fault tree for the established top event. Form the fault tree by using symbols for events, logic gates and transfers. The most commonly used symbols for the formation of the fault tree are given in (Vesely, 2009). Power of a fault tree symbolism lies in the fact that the symbols for events, coupled by logic gates, can easily be translated into algebraic expressions.
6) Checking and adoption of the fault tree. If the fault tree does not reflect the real state, or all significant events are not included, or there is no logic relation

between the basic and top event, then an additional collecting of system data must be performed, as well as modification of the fault tree.

7) Qualitative and/or quantitative analysis. Depending on the final objective of the application of this method, there could be performed a qualitative and/or quantitative analysis, when the fault tree was adopted. Determining a set of minimum intersections of events is the basis for most of the fault tree analysis of the quantitative type.
8) Determine appropriate corrective measures. Based on obtained and adopted results through the fault tree, one should provide suggestions for corrective measures aimed at eliminating the perceived defects or proposals for alternative solutions. Also, decisions have to be made about controlling the manufacturing process or taking risks.
9) Any change in the project should be accompanied and verified by an updating of the formed fault tree and related analysis.
10) Prepare documentation of the analysis process and follow up on identified corrective measures.

In the following basic approach, the development tree, analysis and eventual recommendations for corrective actions are presented as separate steps. In actual practice, there is a great deal of interactions between the steps listed. As a result, the fault tree that evolves includes additions and/or changes reflecting an improved understanding of the various faults.

3. Formation and Analysis of the Fault Tree of Solar Concentrator

The solar concentrator with electric and hydraulic installation represents a system that consists of three subsystems. The analysis of the operation mode of this device led to the conclusion that the failure of any subsystem leads to system failure. This means that the components of the solar concentrator, in terms of reliability, have a serial connection. The block diagram of reliability is presented in Figure 1, and Figure 2 shows the fault tree of this device.For making of the solar concentrator's fault tree, symbols for events and logical gates are used (Vesely, 2009). A rectangle represents the peak or intermediary event in the fault tree, a triangle - primary basic event and a rhomb - secondary basic event. Of all logical gates, only a symbol for logical gate OR was used, which produces an output event if one or more input events occur.

Figure 1. Block diagram of reliability of the solar concentrator with installations

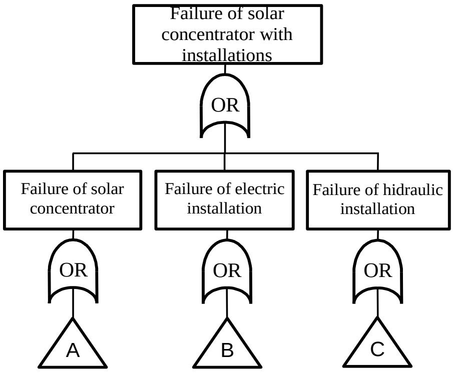

Figure 2. The parent fault tree for the peak event "Failure of the solar concentrator with installation"

It is well known that for the serial connection of elements in the reliability block diagram, the system's reliability is lower than the reliability of the weakest links within the chain.Therefore, it is important, still in the phase of designing of the solar concentrator with installations, to conduct appropriate analyses to find critical elements that have appropriate affect on the reliable and safe operation of the entire system. The analysis of the causes of failure of critical elements enables determination of the measures for complete elimination the causes of failure or to minimize a consequence of failure.

On the basis of technical documentation, detailed introduction with the structure of the solar concentrator system with hydraulic and electrical installation was performed. Dismember scheme of solar concentrator is shown in figure 3.

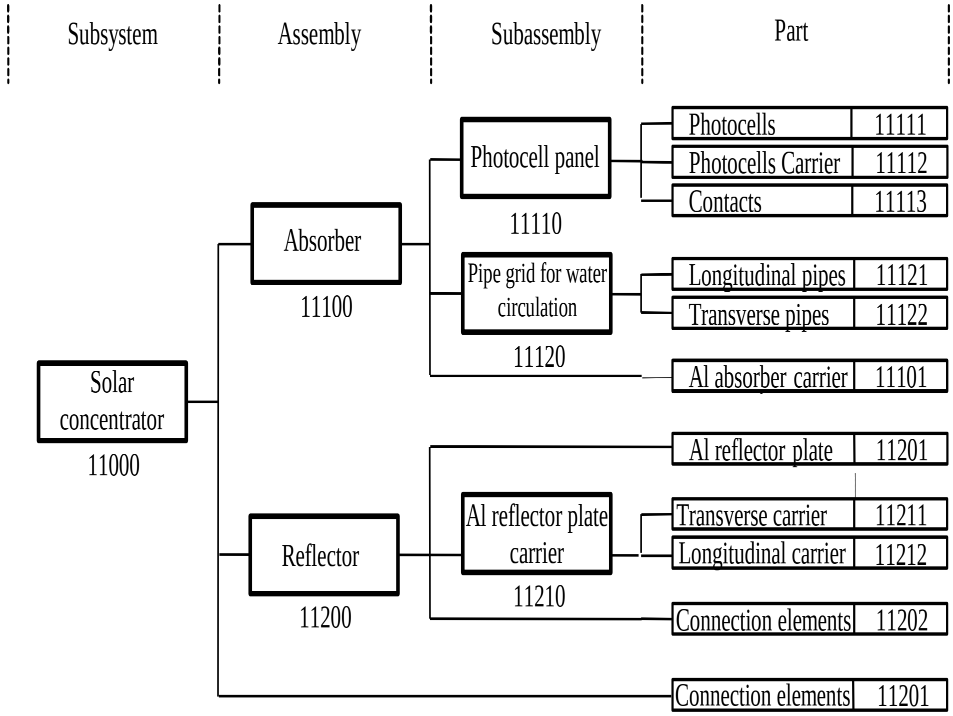

Figure 3. Scheme of dismembering of the solar concentrator

The functional approach was used for the creation of the fault tree of solar concentrator. Peak event in the fault tree, that is shown in Figure 4, is defined as "Failure of the solar concentrator," what meant the complete or partial loss of operating ability of the considered devices.The intermediate events are defined in such a way how the failure of the solar concentrator is observed i.e., using the features of failure.

By considering individual failure modes of solar concentrator's elements it can be determined that all causal events, that lead up to the peak event, can be classified into two under-peak intermediate events: reduction of solar concentrator's efficiency and failure of absorber's elements due to high temperature.

Deductive analysis of these events was done by updating the structure of the fault tree with causes that lead to them in the form of a branches of the fault tree. In this way, in addition to identifying and recording potential failure modes of solar concentrator, a cause-and-effect link between basic, intermediate and peak event is established.

Development of an intermediate event "Reduction of the solar concentrator's efficiency" to basic primary and secondary events is shown in Figure 5 as an independent sub fault tree.

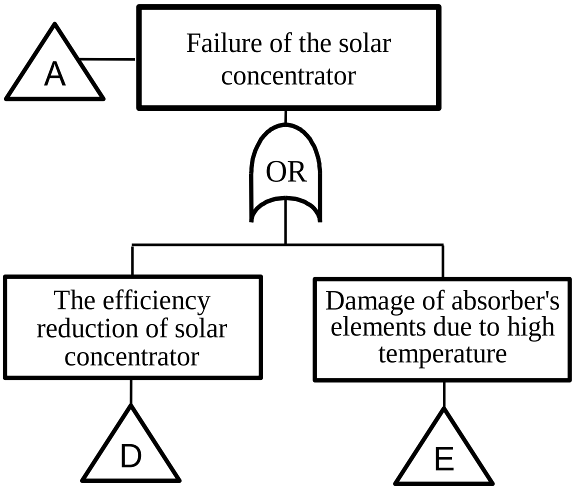

Figure 4. Fault tree of the solar concentrator

The reduction of the solar concentrator's efficiency occurs due to:

- Contamination of the solar concentrator's surface,
- Mechanical damage of solar concentrator's elements or
- Changing the position of the absorber relative to the reflector.

Contaminationof reflector's surface and photocell panel (absorber) may occur due to dust from the atmosphere, the various ingredients of rain and snow that after evaporation of water remains on the surface of the aluminum sheet and photocell panels.Moisture resulting from condensation of water from atmosphere on metal surfaces, can affect the creation of a solid layer of dirt on working surfaces of solar concentrator's reflector and absorber. It is therefore, necessary during the operation of the solar concentrator to provide periodic washing and cleaning of these items.

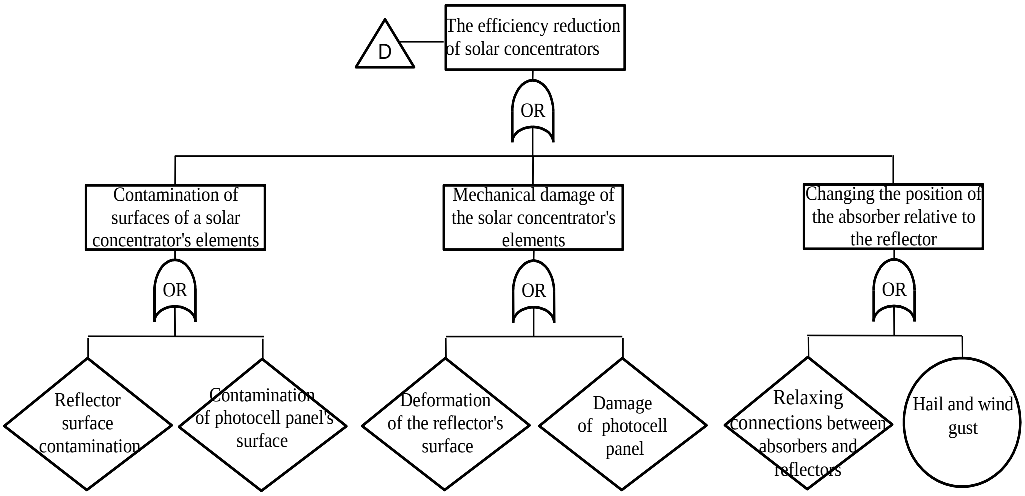

Figure 5. An independent sub fault tree for the peak event"Reduction of the solar concentrator's efficiency"

The term mechanical damage of the solar concentrator's elements implies damage (deformation) of the reflector's surface or damage of photocell panel.The causes of these events may be different. If the solar concentrator is not protected (for example, by placing on the building roof with a transparent cover or on the building wall with glass protection), a big hail can lead to distortion of the reflective surface of the solar concentrator or even damage of the photocell panel. Deformation of the reflector leads to diffusion of light and a significant reduction of the concentration coefficient.

If the solar concentrator is exposed to wind gust, strong wind can lead to crack of the connection elements of aluminum sheet and the reflector's carriers and the partial or total destruction of the reflector sheet and photocell panel. Therefore, it is necessary to pay attention that the mounting of a solar concentrator is performed in places that are sheltered and protected from the wind.

Depending on a connection type between the absorbers and reflectors, the impact can lead to the position change, i.e. turning around of the absorber around connection line with reflector and reduced work efficiency.

If the mounting of the solar collector is well done, it is unlikely that there will be a change in the position of the whole device in space relative to the optimum position. However, given the predicted lifetime of the device is tens of years, it is necessary to apply the sufficiently reliable and safe solution for mounting the solar concentrator.

Due to high temperatures, the damage of the photocell, contacts or electric lines of the absorber can occur. Absorber overheating can occur if the heat generated due to the concentration of light in the absorber is not being conducted away.In the designed solar concentrator, heat dissipation is done by water circulation.Consequently, the solar concentrator overheating can occur if there is no water circulation, or if the temperature of the coolant in the heat exchanger is high or if the water flow is insufficient to cool the absorber. If we bear in mind that copper water pipes of the accepted solution of the absorber, are placed below photocell's panel (not performing convection flow of photocells), it is necessary to check whether it is possible in this way equally cool all points of the photocell's panel.

Independently sub fault tree for the event: "Failure of absorber's elements due to the high temperature" is shown in Figure 6. Failure of the absorber's elements due to the high temperature, or overheating of the photocell's panel, can arise when it comes to:

- Complete lack of coolant circulation,
- If the temperature of the coolant in the heat exchanger is high or
- Lack of coolant flow.

Based on the sub fault tree shown in Figure 6, it can be concluded that this sub fault tree is not an independent. Specifically, the occurrence of peak event in the sub fault tree is mainly under the influence of components of hydraulic and electric installation. Detailed analysis of potential failure modes of hydraulic and electrical installation was done separately. Using a functional approach, in this part of the analysis, only events that cause the occurrence of intermediate events are listed.These events are not developed to their own causes.

Potential failure modes of the hydraulic pump depend on the pump type and it will not be discussed here in detail. Furthermore, failure of electric motor is left as an undeveloped event (diamond). As for the electric power supply, it may be from the city network or from the solar concentrator. If the electricity from the city's network is used, there should be alternative sources, because in 40 years of the predicted lifetime of the solar concentrator, a power outage is likely to happen and will be no circulation of coolant in the absorber when it is necessary. Supplying electric motor of the hydraulic pump with power from the solar device requires additional devices in electrical installation, complicate the construction and thus reduce the reliability of the entire device.Potential failure modes of the hydraulic pump depend on the pump type and it will not be discussed here in detail. Furthermore, failure of electric motor is left as an undeveloped event (diamond). As for the electric power supply, it may be from the city network or from the solar concentrator. If the electricity from the city's network is used, there should be alternative sources, because in 40 years of the predicted lifetime of the solar concentrator, a power outage is likely to happen and will be no circulation of coolant in the absorber when it is necessary. Supplying electric motor of the hydraulic pump with power from the solar device requires additional devices in electrical installation, complicate the construction and thus reduce the reliability of the entire device.

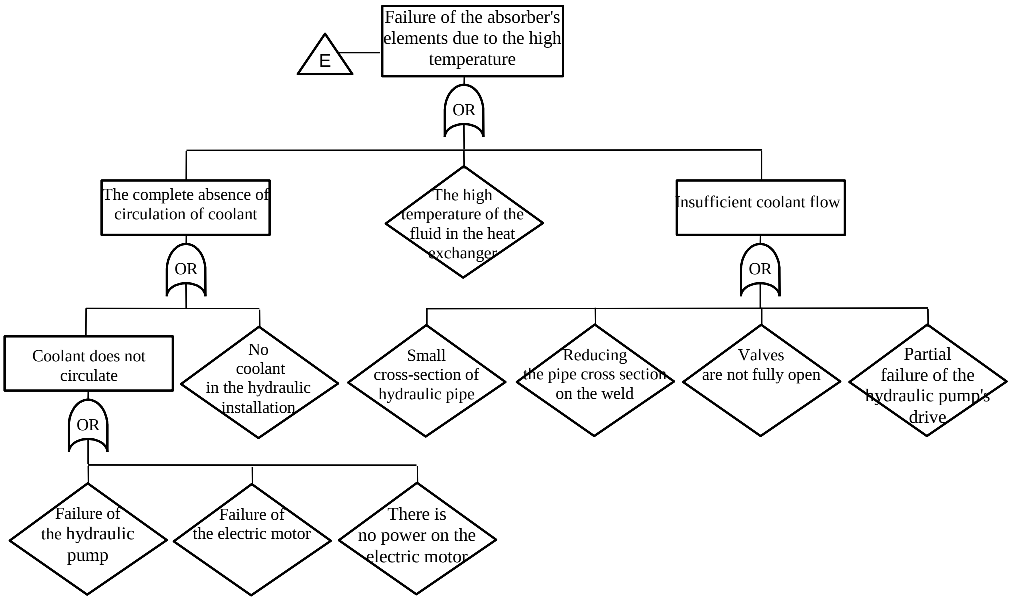

Figure 6. Sub failure tree for the peak event "Failure of the absorber's elements due to the high temperature"

Potential failure modes of the hydraulic pump depend on the pump type and it will not be discussed here in detail. Furthermore, failure of electric motor is left as an undeveloped event (diamond). As for the electric power supply, it may be from the city network or from the solar concentrator. If the electricity from the city's network is used, there should be alternative sources, because in 40 years of the predicted lifetime of the solar concentrator, a power outage is likely to happen and will be no circulation of coolant in the absorber when it is necessary. Supplying electric motor of the hydraulic pump with power from the solar device requires additional devices in electrical installation, complicate the construction and thus reduce the reliability of the entire device.

High coolant temperature at the entrance of the absorber can occurs if the heat exchanger (combine boiler) not performed cooling.In this way, liquid with a high temperature comes in the absorber and there is no possibility for adequate heat dissipation and lowering the temperature of the absorber.

Insufficient flow of coolant can be resulted from: small cross section of hydraulic pipes, reduction of the cross section at welded joints, valves are not fully open, partial damage of the hydraulic pump.

4. Conclusion

By using the FTA- method, detailed analysis of technical systems from the aspect of failures, could be performed. Obtained data makes possible a complex recognizing of causes and modes of failures and also mutual dependence between particular potential modes of elements' failures.

Fault tree presents convenient means for illustration of advantages of proposed solution, in regard to other solutions i.e., it is material for argumentative discussion. If designed system has errors, fault tree could help to find weak spots and it could show how these spots cause the unwanted event.

By adopting the sufficiently general top events in the fault tree and by its development to the basic events, the majority of the potential modes of failure of components can be recorded, which can be, inter alia, used as one of the best Failure Modes and Effects Analysis model for analyses of causes and consequences of faults.

References:

Bojic, M., Catic, D., Matijevic, M., & Miletic, I. (2007).*Geometry of a solar concentrator for heat and electricity production (Project 273003)*, Energetika, Efikasnost, Ekologija, 13. Simpozijum termičara Srbije, Sokobanja, Zbornik radova, c. 1-6.

Bojic, M., Catic, D., Matijevic, M., Miletic, I., & Stefanovic, V. (2008).*Design a stationary asymmetric solar concentrator for heat and electricity production*, Procedings of the Fourth LASTED International Conference Power and energy systems, April 2-4, Langkawi, Malaysia, 341-346.

Dhillon, B. S. (1985). *Quality Control, Reliability, and Engineering Design*, Marcel Dekker, Inc., New York.

Ericson, C.A. (2005).*Fault Tree Analysis, Chapter 11 in: Hazard Analysis Techniques for System Safety*. John Wiley & Sons, Inc.

Fault Tree Analysis (pdf), Electronic Reliability Design Handbook (1998). B. U.S. Department of Defense. MIL–HDBK–338B. http://www.everyspec.com/MIL-HDBK/MIL-HDBK+(0300+-+0499), Retrieved from:/download.php?spec=MIL-HDBK-338B. 015041. pdf. Retrieved 2010-01-17.

Haasl, D.F. (1965). *Advanced Concepts in Fault Tree Analysis. System Safety Symposium*, University of Washington Library, Seattle.

Hixenbaugh, A.F. (1968). *Fault Tree for Safety*. The Boeing Company, D6-53604, Seattle, Washington.

Roberts, N. H., Vesely, W.E.,Haasl, D.F., & Goldberg, F.F. (1981).*Fault Tree Handbook*, Nuclear Regulatory Commission, U.S. Government Printing Office, Washington, D.C.

Stationary solar hybrid concentrator for generation of electricity and heat, Elaborat, Faculty of Mechanical Engineering at Kragujevac, 2007.

Strebkov, D., Tyukhov, I., Vignola, F., Clouston, S., & Rogers, R.(2007).NEW solar combined concentrator TECHNOLOGY IN OREGON. *Oregon institute of technology*,Retrieved from:*oit.edu/adx/aspx/adxGetMedia.aspx?DocID=4202,2769,7,1,Documents&MediaID = 1585&Filename=igor4+ases.doc.*

Vesely, W. (2002). *Fault Tree Handbook with Aerospace Applications.* National Aeronautics and Space Administration. Retrieved 17 January 2010 from: http://www.hq.nasa.gov/office/codeq /doctree /fthb.pdf

Watson, H.A. (1961).*Launch Control Safety Study*, Bell Labs, Murray Hill, NJ,*1*(4).
Yang, G. (2007).*Life Cycle Reliability Engineering*, John Wiley & Sons.

Dobrivoje Catic
University of Kragujevac
Faculty of Engineering,
Kragujevac
Serbia
zdravkok@ac.me

Milorad Bojic
University of Kragujevac
Faculty of Engineering,
Kragujevac
Serbia
bojic@kg.ac.rs

Jasna Glisovic
University of Kragujevac
Faculty of Engineering,
Kragujevac
Serbia
jaca@kg.ac.rs

Zorica Djordjevic
University of Kragujevac
Faculty of Engineering,
Kragujevac
Serbia
zoricadj@kg.ac.rs

Nada Ratkovic
University of Kragujevac
Faculty of Engineering,
Kragujevac
Serbia
nratkovic@kg.ac.rs