UNIVERSITY OF PETROSANI

DOCTORAL SCHOOL

Field: INDUSTRIAL ENGINEERING

DOCTORAL THESIS

-SUMMARY-

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DOCTORAL STUDENT:
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INCREASING THE LEVEL OF SECURITY IN THE TRANSPORTATION OF HAZARDOUS GOODS

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CONTENT

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1. Concepts, Definitions, Thesis Motivation, Pursued Objectives

The thesis "Increasing the Level of Security in the Transportation of Hazardous Goods Activity" addresses an extremely current research topic in the era of industrial transport within the context of the globalization of activities conducted at locations and routes designated for specific operations involving hazardous substances. It presents an applied study method harmonized with the current requirements in the field of hazardous substance transportation, from the perspective of the continuous improvement of the security climate affected by the presence of associated dangers.

The theoretical and practical foundation of the methods for increasing the level of security in the transportation of hazardous goods activity involved the following research efforts:

-Analysis of Applicable Regulations Established at the International and National Levels Regarding ADR Transport;

-Research on the phenomenon that can occur during the transition from deflagration to detonation and the possibility of determining this phenomenon;

-Study of the Establishment of Civilian Explosives Equivalence;

-Evaluation of Industrial Risk Specific to the Transportation of Hazardous Substances;

-Establishment of Technical Solutions for Securing ADR Transport;

-Highlighting the Technical Aspects Specific to the Optimization of ADR Transport;

-Establishment of Measures for Preventing and Reducing the Aggressiveness of Hazardous Goods on the Environment.

The motivation for the doctoral thesis is related both to the necessity of optimizing the methodological infrastructure for estimating and assessing the specific risks of ADR transport and to the development of applicable technical solutions and best practices regarding the calculation of safety systems and the logistics associated with this type of transport, with the aim of enhancing its safety on dedicated routes while ensuring effective management of security quality in this field.

The main objectives of the thesis consist of conceptualizing the risk assessment mechanism specific to ADR transport, as well as developing technical solutions and best practices for enhancing security when hazardous substances are involved, based on the results of conducted technical and scientific research. These fundamental objectives are achieved through *derived objectives*, namely: analysis of the general regulatory aspects regarding the transportation of hazardous goods; study of the transition phenomenon from deflagration to detonation exhibited in the behavior of hazardous materials (Class 1); establishment of equivalence for civilian explosives; estimation and assessment of the specific risks of ADR transport; and the establishment of technical solutions for increasing safety in the transportation of hazardous goods.

The derived objectives are fulfilled based on the *primary objectives*, namely: studying the bibliographic material dedicated to the thesis topic through reading and analyzing references and notes specific to the area of interest; conceptualizing the term "hazardous goods"; conducting technical and scientific research on evaluating the degree of danger associated with solid substances in terms of explosion risk; scientifically investigating the transition phenomenon from deflagration to detonation and highlighting methods for determining it; preliminary tests on the combustion behavior of specific solid hazardous substances; establishing the equipment and materials necessary for setting up the testing stand to conduct tests on the transition from deflagration to detonation of hazardous materials from Class 1 according to the Orange Book; configuring the setup for the transition test from deflagration to detonation and conducting pilot tests for hazardous materials (Class 1); theoretical and practical considerations regarding the determination of the relative working capacity of civilian explosives; experimental determination of the working capacity of explosives; synthetic presentation of the results of pilot tests conducted; methodology for establishing the equivalence of civilian explosives using standard ANFO; development of the procedure for

determining the relative working capacity of civilian explosives using standard ANFO; highlighting theoretical aspects related to the specific risks of transporting hazardous goods; studying exposure due to the road transport of hazardous goods; research on territorial compatibility in areas adjacent to routes designated for hazardous goods transport; exemplifying a quantitative analysis of individual and societal risk at the local level; current status regarding the management and risk assessment of ADR transport; hazardous goods and ADR transport; regulations of ADR transport; estimation and assessment of specific risks in ADR transport; optimization of ADR transport management; solutions for securing ADR transport; measures to combat the negative environmental effects generated by the aggressiveness of hazardous goods; and applied examples of determinations related to security systems and logistics associated with ADR transport.

The strategic mechanism of the research undertaken to achieve the objectives set for the completion of the thesis focused, from a technical and scientific perspective, on the following major directions of study:

-The introductory section of the thesis highlights the national and international legal framework for regulation within the scope of interest regarding the specific risks of ADR transport when hazardous substances are involved. It establishes normative technical aspects concerning the securing of activities conducted in the presence of associated dangers, in industrial spaces and dedicated transport routes.

-The next step in the research focuses on both establishing the behavior of hazardous materials classified as Class 1 regarding the transition from deflagration to detonation, as well as studying the establishment of equivalence for civilian explosives. Additionally, it involves estimating and assessing the specific risks of ADR transport and developing innovative technical solutions to enhance the safety of this type of transport.

-The final important step of the research involves expressing contributions to the optimization of ADR transport management and establishing measures to combat the negative environmental effects generated by the aggressiveness of hazardous goods.

2. Structure of the Thesis and Some Contributions

Structurally, the thesis comprises an introductory chapter and five thematic chapters, with a concluding chapter for Final Conclusions and Personal Contributions, totaling 194 pages. Of these, 175 pages constitute the main thesis, while 18 pages include the bibliography, which contains 319 bibliographic references, along with specialized annexes.

The valuable contributions developed in the specialized sections of the doctoral thesis are as follows:

-A systematic and integrative highlighting of the national and international normative structure regulating the transportation of hazardous goods;

-The development of a technical and scientific research study examining the behavior of hazardous materials classified as Class 1 concerning the transition from deflagration to detonation;

-The study of the explosion risk generated by the behavior of substances classified as Class 1 according to the Orange Book;

-The scientific investigation of the transitional phenomenon "deflagration-detonation" and the highlighting of methods for its determination;

-The development of a specialized methodology for establishing the equivalence of civilian explosives using "ANFO" Standard;

-The development of a procedure for determining the relative effectiveness of civilian explosives using "ANFO" Standard;

-The study of exposure due to the road transport of hazardous goods;

-The estimation and assessment of the specific risks associated with ADR transport;

-Research on territorial compatibility in the areas adjacent to transport routes designated for hazardous goods;

-An example of a quantitative analysis of individual and societal risk at the local level;

-The establishment of technical solutions for securing ADR transport;

-The establishment of constructive and functional requirements specified by the applicable regulations for ADR transport infrastructure;

-The quantification of the risks associated with ADR transport;

-The establishment of measures to mitigate the negative environmental effects generated by the aggressiveness of hazardous goods;

-The highlighting of the technical aspects specific to the optimization of ADR transport.

-The configuration of optimization criteria for the management of ADR road transport;

-The determination of specific algorithms for the logistics associated with the transportation of hazardous goods;

-Experimental trials and tests on the internal combustion behavior specific to solid hazardous substances;

-Practical examples of determinations related to security systems and the logistics associated with ADR transport;

-The development of an applied technical solution for optimizing the management of hazardous substance transport based on the five influencing criteria (distance, risk of environmental pollution in case of a road incident, number of potentially affected individuals, state of infrastructure, and traffic difficulty), utilizing the features of the ELECTRE III software application;

-Specialized applications for calculating safety systems and the logistics associated with the transportation of hazardous goods.

The valorization of the technical-scientific results of the conducted research was achieved through their dissemination in the proceedings of various conferences/symposia or in recognized ISI or BDI journals.

3. Thesis Summary

Given the pronounced dynamics of a modern society that continuously restructures its fields of work, various risks specific to the sectoral activities carried out at the national economy level arise. In the current context, with the intensification of ADR transport, there has been an increase in the number of events at the international level that have had a significant impact on both human factors and environmental components, also manifesting economically.

The doctoral thesis titled *Increasing the Level of Security in the Transportation of Hazardous Goods* comprises 7 chapters, which are presented succinctly below.

Chapter 1, *Introduction*, highlights general aspects, the pursued objectives, the motivation for the doctoral work, and a concise descriptive overview of the thesis.

In Chapter 2, titled *General Regulatory Aspects Regarding the Transportation of Hazardous Goods*, I provided a summary of the national and international legislative framework specific to accident risk when hazardous substances are involved, applicable to economic operators in the ADR transportation sector. In this regard, the field of hazardous goods is regulated globally, at the European level, and nationally through specific regulations aimed at the proper management of risks associated with these types of products, namely the ADR regulation concerning the international road transport of hazardous goods and the ORANGE BOOK, which pertains to testing methods and criteria necessary for classifying hazardous substances.

Considering that hazardous goods classified under the Orange Book are transported worldwide, a global approach to their transportation and storage rules is necessary, as major risks primarily manifest during their transport. Additionally, the proper classification and categorization of substances and objects in "Class 1 - Explosives" are based on a series of tests described by ADR, which were briefly presented in Chapter 2, with a focus on Test Series 5, which assigns divisions from 1.1 to 1.6.

Chapter 3 is titled "*Study of the Transitory Phenomenon 'Deflagration-Detonation' Manifested in the Behavior of Hazardous Materials (Class 1).*" This chapter presents an analysis of the combustion process of hazardous substances classified in Class 1 according to the Orange Book, focusing on determining whether they exhibit deflagrant or detonant characteristics, depending on their presentation, confinement level, environmental conditions, and chemical purity. The theories regarding ignition and the development of combustion reactions in materials with energetic properties have significantly evolved over the past two decades, driven by an increase in experimental knowledge. It is important to note that the reaction processes occurring in these materials can be complex, as they represent a multidisciplinary interaction between thermodynamics and kinetics, with the final outcome constituting a functional relationship dependent on the main parameters of the physicochemical process: pressure, temperature, and time. To analyze the combustion behavior of solid hazardous substances, a series of tests were conducted at the INSEMEX explosive testing polygon on three types of substances: porous ammonium nitrate, ANFO explosive mixture, and gel explosive.

In the case of the first experiment, it was observed that the burning of the powder used as an open flame source led to partial melting in the contact area between the powder and the material being tested (porous ammonium nitrate), without the combustion being self-sustaining; the flame extinguished spontaneously without exhibiting the tendency for deflagration or detonation.

In the case of the second experiment, where ANFO was used, the sample subjected to testing was more significantly affected by the ignition source, as the flame exhibited a tendency to sustain itself. A substantial part of the sample burned, resulting in the formation of a crust of melted and partially decomposed material in the area of contact with the flame. Additionally, after a period of time, the flame extinguished itself, with a portion of the charge not visibly affected by the thermal effect. In this situation, there is no question of analyzing the phenomenon of transition from slow combustion to a violent deflagration or detonation.

As a result of the third experiment, the explosive subjected to testing ignited, burning with a slow propagation tendency and complete decomposition over time, without any observation of the transition from combustion to violent deflagration or detonation.

Analyzing the results obtained from the three experiments, it is evident that hazardous materials classified as Class 5.1 oxidizers, Class 1.5 high initiation-capacity explosives, and even Class 1.1 high-power explosives with a high sensitivity to stimuli, when burned in open spaces or with reduced confinement (V-shaped trough), burn with an open flame, with or without a tendency for self-sustained combustion, and there is no risk of detonation occurring as a result of the fire.

The experiment to verify the pyrotechnic initiators based on their detonative initiation capacity demonstrated that the electric initiator, despite its significant incendiary power, was unable to trigger the detonation of a high-power explosive based on hexogen. Instead, the test cartridge ignited and burned at a constant rate with an open flame.

Chapter 4, titled "*Contributions to Establishing the Equivalence of Civil Explosives,*" focuses on the detailed description and development of requirements for creating a standard ANFO explosive mixture with a high level of reproducibility. This is aimed at establishing the equivalence of civil explosives in terms of their relative working capacity using standard ANFO. The working capacity, or potential of explosives, is a crucial ballistic parameter used for comparing explosives regarding their displacement potential under production conditions. This can be determined through various methods, including the Trauzl test, ballistic mortar test, Hess test, and crater rupture tests, among others.

Following a critical analysis of the methods used to determine the relative working capacity of civil explosives, and considering the technical disadvantages, high costs, and low reproducibility associated with other methods, the advantages of using the ballistic pendulum method were highlighted as an alternative for determining the working capacity or potential of explosives using standard ANFO. To conduct experimental tests, a perfectly reproducible "ANFO" mixture was

created under laboratory conditions, meeting the reference material requirements for comparative testing. After conducting a series of specific tests on samples of "ANFO" explosive mixtures prepared in the laboratory, the composition regarding the homogeneous physical-chemical and ballistic characteristics was established and validated, resulting in its classification as a "standard." The results obtained from the statistical data processing of the measurements indicated that when performing "CRL" determinations with TNT standard and "CRL" with ANFO standard, the differences from the average value were less than 7.41% (TNT standard) and 4.64% (ANFO standard).

The aspects related to *Contributions regarding the analysis and evaluation of industrial risk specific to the transportation of hazardous substances* are highlighted in **Chapter 5**. In this chapter, I proposed an original, complex grid that considers incidents in road traffic and their potential effects on both people and the environment. The proposed evaluation sheet contains six criteria, each assigned a score between [0...5]. By summing the partial scores, a total score ranging from [0...30] is obtained. Depending on the total score, six risk levels are proposed: very low, low, moderate, high, and very high. Completing the grid leads to the conclusion that ammonia is a hazardous substance with a high risk. As an alternative, a risk calculation used in management is presented, adapted to the specific situation of hazardous substances. The three independent variables of the calculator (probability, exposure, and consequences) are associated with the likelihood of an accident occurring, the exposure of people to the hazardous substance, and the consequences of the accident on life. For the same example of ammonia, a similar degree of risk (high) is obtained, demonstrating that a generalized risk calculation brief can be used, provided that logical values are correctly assigned, with the advantage being the speed of obtaining the result.

I also proposed an initial mathematical model for evaluating the risk associated with the transportation of hazardous goods. The model is based on the following working hypotheses: the transport route consists of multiple segments, each with a different potential for incidents; on a given segment, the average number of accidents per kilometer is constant; although traffic is very congested, accidents or incidents are statistically rare events; the risk associated with traversing a route results from the sum of the risks recorded on the component segments. Under these conditions, a model based on the exponential distribution is proposed, as it is known to describe rare events. The model incorporates the lengths of the segments of a route and the accident rates specific to each segment, resulting in the overall risk for the entire route. A numerical example is also presented to illustrate the practical application of the model.

In **Chapter 6**, titled *Contributions Regarding the Establishment of Technical Solutions for Increasing Safety in the Transportation of Hazardous Goods,* a synthesis of the constructive and functional characteristics of hazardous goods transportation systems is presented, as mandated by legislation. It is noted that safety elements primarily concern the materials from which parts or subassemblies that come into direct contact with or are near the transported hazardous substances are made, as well as the general measures applicable to the vehicle's electrical system. These measures aim to prevent overheating or to shield against heat transfer within the transport compartment. It follows that these general elements need to be supplemented with specific systems tailored to each type of substance (potentially generalized by class), which are not included in the standard vehicle model, except for tanks designed for specific types of transport. Additionally, I proposed two constructive solutions designed for operation within an automated continuous monitoring system for the parameters defining danger, allowing for immediate and rapid intervention in the event of an incident, while simultaneously alerting the necessary emergency units through the e-Call system.

The first solution is based on the volumetric diffusion of neutralizing material for hazardous substances or extinguishing fire outbreaks through nozzles attached to a main pipe, fixed to the longitudinal wall of the airtight container. The neutralizing/extinguishing material is stored in a special reservoir included in a hydraulic system, equipped with a pump and secondary fluid circulation pipes. The volumetric coverage of the container's interior is ensured by a mechanical oscillation system for the main pipe, which includes a gear motor and stroke limiters. The second

solution proposes a trolley system equipped with two wide nozzles that eject the active material in the form of jets, traversing the length of the container with the help of an electric drive system and a rolling mechanism, on which the guide roller and support rollers roll. Both solutions foresee the collection of the reaction material between the vapors of the hazardous substance and the neutralizing fluid, or the residues of combustion combined with the extinguishing material, in a chemically neutral grating system filled with absorption sponges for the products collected on the floor of the container. The two solutions are analyzed comparatively based on technical and economic efficiency criteria.

In the final part of the chapter, a proposal is developed regarding the enhancement of safety in the transport of hazardous materials through the implementation of educational measures. At the national level, the safety of ADR transport can be improved through investments in specific safety systems and the initiation of training measures for those who handle such substances. Reducing risk cannot solely rely on transport operators, who lack the financial capacity and means to enforce appropriate procedures; state involvement through its relevant agencies is also essential. Currently, these agencies exist but do not operate effectively.

Chapter 8 - *Final Conclusions and Personal Contributions* highlights the valuable contributions made to enhance safety in the transport of hazardous materials, concerning: the conceptualization and configuration of methodological mechanisms for analyzing and evaluating accident risk specific to the transport of hazardous substances; the evaluation of the behavior of hazardous materials (Class 1) regarding the transition from one state (deflagration) to another (detonation); the establishment of equivalence for civil explosives; the development of technical solutions for securing ADR transport; as well as the methodological aspects of addressing the optimization of hazardous materials transport.

4. Personal Contributions

4.1. - Theoretical Contributions

The theoretically valuable results, as a personal contribution, which were highlighted in the body of content of the doctoral thesis, are:

-Study of the specialized literature based on an integrated analysis of the main sources of documentation related to the legislation on the transport of dangerous goods.

-Conceptual grounding of the behavioral evolution specific to dangerous substances (Class 1) in terms of the transitional character (deflagration – detonation).

-Study of the explosion risk generated by the behavior of substances classified in Class 1 according to the Orange Book.

-Analysis of the phenomenon that can occur during the transition from deflagration to detonation and the possibility of determining it;

-Development of a specialized methodology for establishing the equivalence of civil explosives using "ANFO" as a benchmark;

-Development of a procedure for determining the relative working capacity of civil explosives using "ANFO" Standard;

-Comparative study of exposure resulting from regional ADR road transport and evaluation of critical infrastructure risk;

-Evaluation of industrial risk specific to the transport of hazardous substances;

-Study of territorial compatibility in the vicinity of routes designated for ADR transport;

-Establishing technical solutions to enhance safety in the transport of hazardous goods;

-Establishing the construction-functional characteristics mandated by legislation for hazardous goods transportation systems;

-Modeling the risk associated with the transportation of hazardous goods;

-Establishing the measures to prevent and reduce the aggressiveness of hazardous goods on the environment;

-Study of optimizing the management of hazardous goods transportation.

4.2. -Experimental and applicative contributions.

The significant results of this type, which have been documented in the doctoral thesis, are:

-Experimental trials and tests on the specific internal combustion behavior of solid hazardous substances:

- ✓ experimental tests on the combustion behavior of various explosive materials: porous ammonium nitrate (risk class 5.1, according to the Orange Book), ANFO explosive mixture (risk class 1.5, according to the Orange Book), and explosive gel (risk class 1.1, according to the Orange Book);
- ✓ tests regarding the non-detonation verification of explosives during the operation of pyrotechnic igniters.

-The development of technical solutions to increase the safety of the road transport of dangerous goods that ensure the detection and neutralization of accumulations of dangerous substances, regarding the extinguishing of fires in the loading compartment of a vehicle transporting dangerous goods, respectively:

- ✓ *mechatronic safety system (solution 1)*, designed as a safety system attached to vehicles transporting hazardous goods in containers, operating on the principle of the oscillating rotation of the main pipe with nozzles around its own axis;
- ✓ *mechatronic safety system (solution 2*), designed to enhance the safety of hazardous goods transport, based on the main spraying movement achieved through the sliding of a sled along the loading compartment.

-Development of an applied technical solution for optimizing the management of hazardous substance transport based on five influencing criteria (distance, environmental pollution risk in case of a traffic incident, number of potentially affected people, infrastructure condition, and traffic difficulty), utilizing the features of the ELECTRE III software application;

-Specialized applications for calculating safety systems and logistics associated with the transport of hazardous goods, focusing on:

- ✓ calculation of the mechanical and hydraulic parameters of the safety system;
- ✓ calculation of the liquid flow rate required to extinguish a fire involving hazardous substances.

4.3-Future Research Directions

Based on the original results obtained in full accordance with the thematic directions of the work, which have been documented as personal contributions, and considering the scientific horizon of interest regarding the identified issues, I highlight the following possible future research directions that can be pursued:

- Digitalization of integrated security systems (biometric recognition, etc.) and verification of the traceability of hazardous substances and dedicated ADR transport routes;
- Modernization of integrated monitoring systems for industrial spaces and transport routes in the ADR field;
- Designing and planning an intelligent industrial space for securing ADR transport and optimizing the safety of transport routes for specific operations involving hazardous substances.