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INFRASTRUCTURE AND ECOSYSTEM FOR THE REGENERATION AND RECIRCULATION OF PROCESS FLUIDS (Modular Architecture of Systems for the Regeneration and Recirculation of Complex Process Fluids, Including Water and Aqueous Solutions)

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Abstract

The article discusses the development of an integrated infrastructure and ecosystem for water treatment, water conditioning, and the regeneration and recirculation of process fluids intended for modern industrial applications. Particular attention is devoted to the creation of a comprehensive modular technology for the treatment of industrial wastewater based on a sequence of autonomous yet technologically coordinated processing stages employing different physical and chemical treatment principles.

The proposed concept is founded on the implementation of complete, standardized, and autonomous technological modules that may be combined into integrated treatment systems depending on the composition, characteristics, and intended reuse of process fluids. Within this framework, each stage of the treatment process performs a specialized technological function while remaining operationally independent, thereby increasing the flexibility, reliability, scalability, and overall efficiency of the system.

The article also examines innovative engineering concepts proposed by *Ostap Victor Vlad*, particularly the hierarchical architecture of specialized technological modules possessing narrow functional specialization, autonomous operating cycles, and the ability to operate without the use of chemical reagents or synthetic activating additives. This modular engineering approach makes it possible to construct higher-level technological systems from lower-level autonomous modules while maintaining maximum technological and economic efficiency.

Special emphasis is placed on reagent-free regeneration technologies that enable the immediate transition from the regeneration process to continuous online recirculation of process fluids. The absence of externally introduced chemical reagents preserves the physicochemical properties of treated liquids, maintains a high level of process-fluid quality, and significantly improves the environmental sustainability and operational efficiency of industrial water treatment systems.

The proposed technological infrastructure, modular architecture, regeneration methods, and process-fluid recirculation technologies are presented as innovative engineering developments with significant practical potential for modern industrial production, environmentally sustainable manufacturing, and advanced water resource management, while also demonstrating substantial prospects for further technological development and intellectual property protection through integrated and combinatorial engineering solutions.
Keywords: *Infrastructure and ecosystem for water treatment and water conditioning; infrastructure and ecosystem for the regeneration and recirculation of process solutions; water and aqueous solutions; integrated technology for the treatment of industrial wastewater based on a sequence of interconnected yet operationally independent processing stages; integrated modular technology implemented through complete, autonomous, and standardized technological modules, in which each stage of water treatment is represented as a sequential processing operation employing distinct physical and chemical treatment principles*

Introduction

At present, various industries that utilize water for technological and manufacturing purposes employ several principal methods for the treatment and purification of water contaminated by industrial products, process by-products, and technological waste streams. The most widely used approaches include the following:

- **Chemical reagent-based water treatment**, encompassing several modifications of this method and its combinations with other treatment technologies. This approach remains the predominant industrial solution, accounting for more than **70%** of the global water treatment technology market;
- **Reagent-free water treatment and purification**, represented by several principal technological modifications that differ in their operational capabilities and performance characteristics. These methods currently account for less than **20%** of the water treatment technology market;
- **Combined treatment technologies**, which generally integrate reagent-based and reagent-free methods together with additional technological processes adapted to specific industrial operating conditions. These technologies currently represent approximately **10%** of the market and continue to demonstrate significant growth potential.

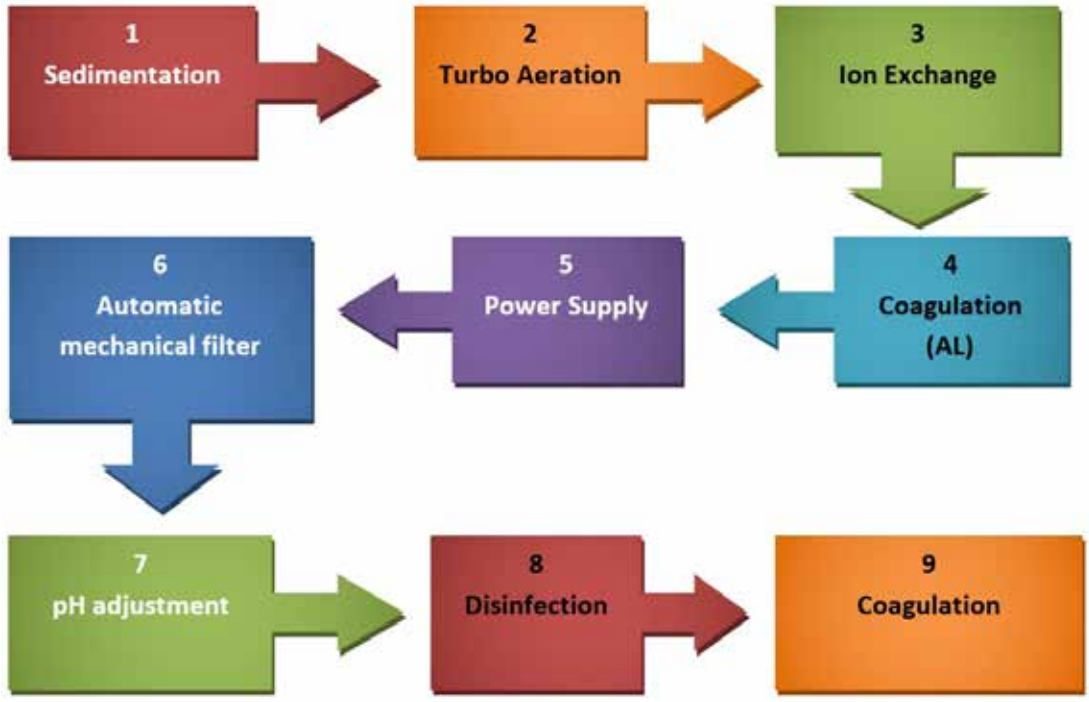
The challenges currently encountered in industrial water treatment and water conditioning can no longer be effectively addressed using conventional technologies alone. Modern industrial production requires comprehensive engineering solutions, as isolated or partial technological improvements fail to satisfy the increasingly stringent environmental, technological, and economic requirements imposed on contemporary manufacturing processes. Consequently, neither individual treatment methods nor existing combinations of conventional technologies are capable of fully meeting the continuously evolving demands of modern industry.

Taking these circumstances into consideration, and building upon recently emerging innovative engineering concepts, the author proposes an integrated technology for the treatment of industrial wastewater based on a sequence of technologically coordinated yet operationally independent processing stages.

More specifically, the complete water treatment process may be considered as a succession of individual treatment operations, each employing a distinct physical or chemical mechanism of action. Every processing stage performs a specialized technological function while contributing to the overall efficiency of the integrated treatment system.

Combining these engineering principles with the latest innovative concepts proposed and published by distinguished technology developer Ostap Victor Vlad, the author presents a comprehensive modular technology implemented through complete, autonomous, and standardized technological modules configured as the following integrated system:

Figure 1. *Diagram of the Nine Principal Modular Technological Configurations Incorporating All Processing Stages and Operations Required for the Formation of a Modular Technological Equipment Complex Intended for the Treatment, Regeneration, and Recirculation of Process Fluids, Including Water and Aqueous Solutions*



Among the modules presented, **Module 5 (Power Supply Unit)** is comparatively universal in its application, whereas the remaining eight modules perform specialized technological functions within the integrated water treatment system.

Module 1 – Sedimentation Module, which may be configured either as a sedimentation column or as a sedimentation tank having a rectangular (parallelepiped) geometry.

Module 2 – Turbo-Aeration Module, which may be implemented in at least two configurations: one utilizing foam generators and another employing an integrated mixing and online homogenization system.

Module 3 – Ion-Exchange Treatment Module, which may be implemented in numerous configurations, one of the most efficient being ion-exchange columns incorporating capsules for ion-exchange resins fabricated from carbon-carbon composite fabrics.

Module 4 – Coagulation Module, utilizing aluminum ions generated within electrochemical reactors equipped with aluminum anodes as the coagulant.

Module 5 – Power Supply Unit, providing electrical power to the technological modules and associated electrochemical processing systems.

Module 6 – Automatic Mechanical Filtration Module, incorporating automatic cleaning of the filtration sections together with online regeneration of the filter elements.

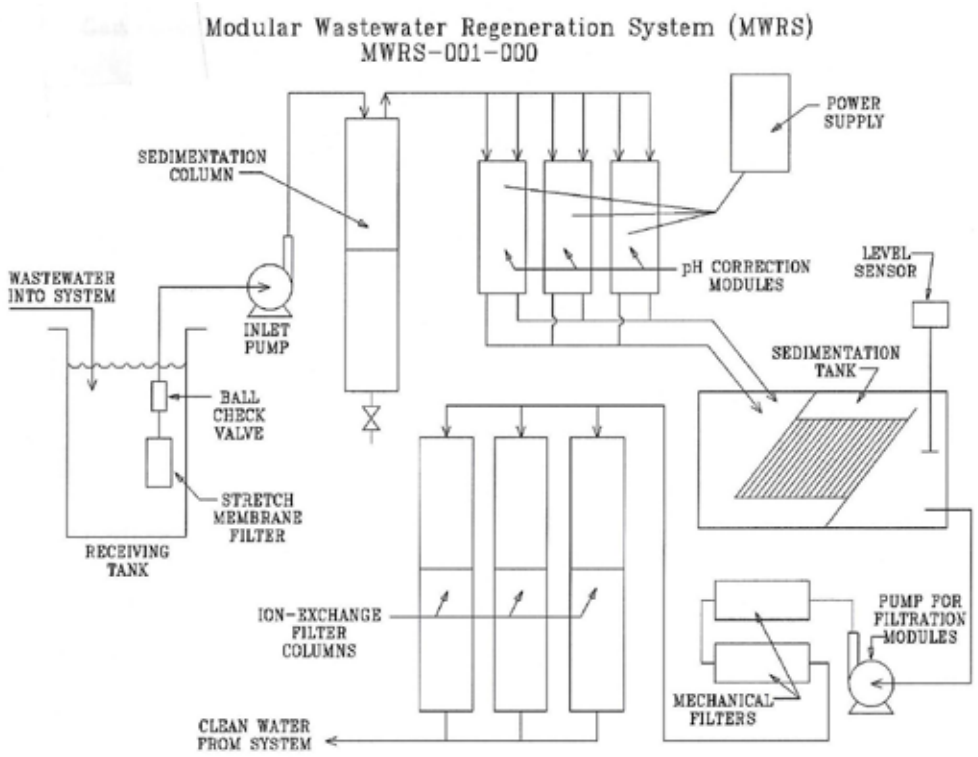
Module 7 – pH Adjustment Module, intended for the regulation and stabilization of the acidity and alkalinity of process fluids.

Module 8 – Reagent-Free Electrochemical Disinfection Module, designed to provide electrochemical disinfection without the addition of chemical disinfectants.

Module 9 – Final Electrochemical Coagulation Module, intended for the final polishing stage of the treatment process through electrochemically induced coagulation.

This modular architecture enables the development of scalable, flexible, and integrated technological systems that can be configured according to the specific requirements of industrial water treatment, process fluid regeneration, and recirculation applications while maintaining high operational efficiency and environmental sustainability.

Figure 2. *Example of a Modular System Configuration for the Regeneration of Process Fluids, Including Water and Aqueous Solutions*



As illustrated in the diagram, the inlet of the system is equipped with a receiving tank incorporating several functional components that perform the preliminary treatment of process fluids that have completed their operational cycle. The incoming liquid first passes through a membrane filter and then, via a check valve, enters the inlet pump, which delivers the process fluid to the sedimentation column. Depending on the required treatment capacity and process flow rate, the sedimentation column may consist of one, two, or three independent sections.

Following the primary sedimentation stage, the process fluid is directed to electrochemical reactors designed to adjust its acidity or alkalinity. These reactors are supplied with electrical power and controlled by a multifunctional power supply unit.

After pH adjustment, intended to establish alkaline conditions that maximize sedimentation efficiency, the fluid enters a specially designed sedimentation module featuring an optimized internal geometry that promotes the separation of sedimentation conglomerates from the liquid within an upward-flow regime.

Upon completion of the sedimentation process, the treated liquid is transferred, under the control of a level sensor, by a centrifugal pump to the automatic mechanical filtration modules, where residual conglomerate particles that have not settled within the sediment layer are removed by mechanical filtration.

Because the mechanical filtration modules operate continuously in an online mode, the discharge pressure generated by the filtration pumps is sufficient to supply the filtered liquid directly to the ion-exchange treatment columns.

Building upon the engineering concepts, technical publications, patent applications, and long-term technological forecasting developed by Ostap Victor Vlad in the field of environmentally sustainable intelligent manufacturing systems, the author of the present study has significantly expanded the technical capabilities and functional characteristics of ion-exchange treatment columns, which deserve further detailed consideration.

Particular attention should be given to the fact that ion-exchange treatment may effectively employ not only synthetic ion-ex-

change resins but also naturally occurring ion-exchange materials, among which zeolite represents one of the most effective alternatives.

Within the innovative modular architecture of ion-exchange columns proposed by Ostap Victor Vlad, where each column consists of at least two independent modular sections, it becomes possible to combine several ion-exchange materials possessing different exchange capacities within a single treatment column. For example, the upper section may contain zeolite, while the lower section may be filled with a synthetic ion-exchange resin.

The combination of these complementary ion-exchange materials provides highly efficient conditions for the purification, regeneration, and recirculation of process fluids while improving both treatment performance and operational flexibility.

This modular configuration has been developed in accordance with the engineering concepts and inventions proposed by Ostap Victor Vlad, a recognized developer of reagent-free technologies for the comprehensive high-intensity treatment of industrial liquids, including water and aqueous solutions, operating under continuous real-time flow conditions.

Practical implementation has demonstrated that the hierarchical system of technological modules proposed and developed by Ostap Victor Vlad, characterized by narrow technological specialization together with a high degree of operational autonomy, independent technological cycles, and the complete absence of chemical reagents or synthetic activating additives, enables higher-level integrated treatment systems to be constructed from lower-level modular components while maintaining maximum technological and economic efficiency.

Furthermore, because no chemical reagents are introduced into the treatment process, the completion of the regeneration stage allows the online recirculation process to commence immediately. This approach preserves the physicochemical properties and consistently maintains a high level of quality of regenerated process fluids and aqueous solutions while substantially improving the environmental sustainability and operational efficiency of the overall treatment system.

Figure 3. *Modular Treatment System Incorporating an Intermediate Module with a Preliminary Inlet Filter and a Series of Mechanical Filters Installed Downstream of the Intermediate Module and Upstream of the Electrochemical Reactors for pH Adjustment*

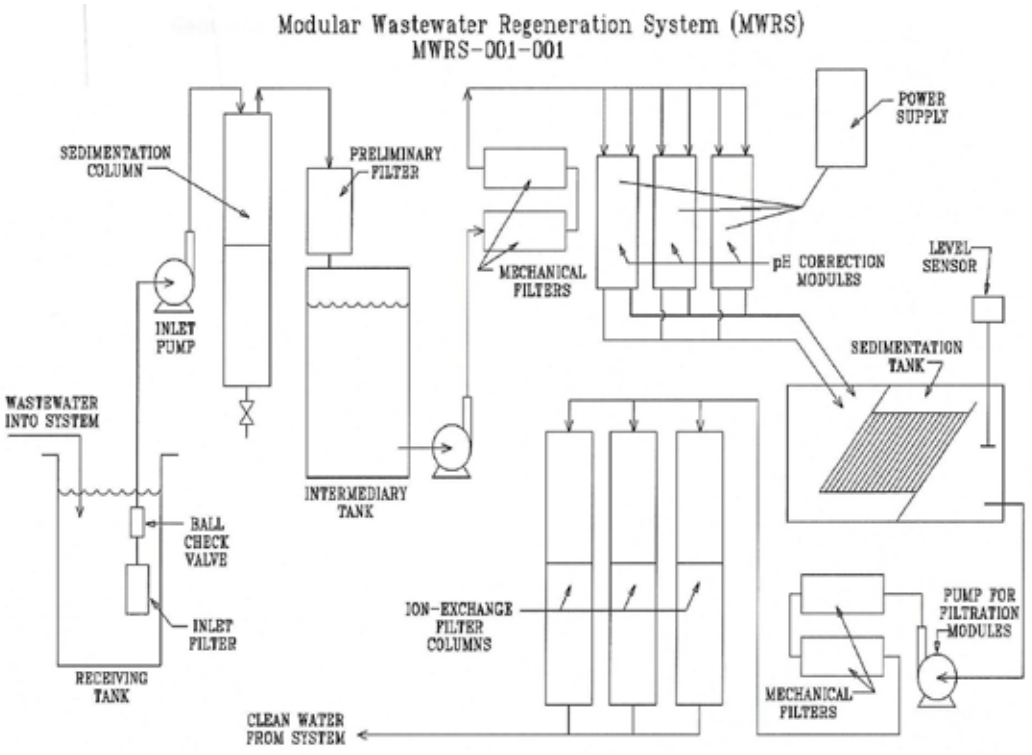
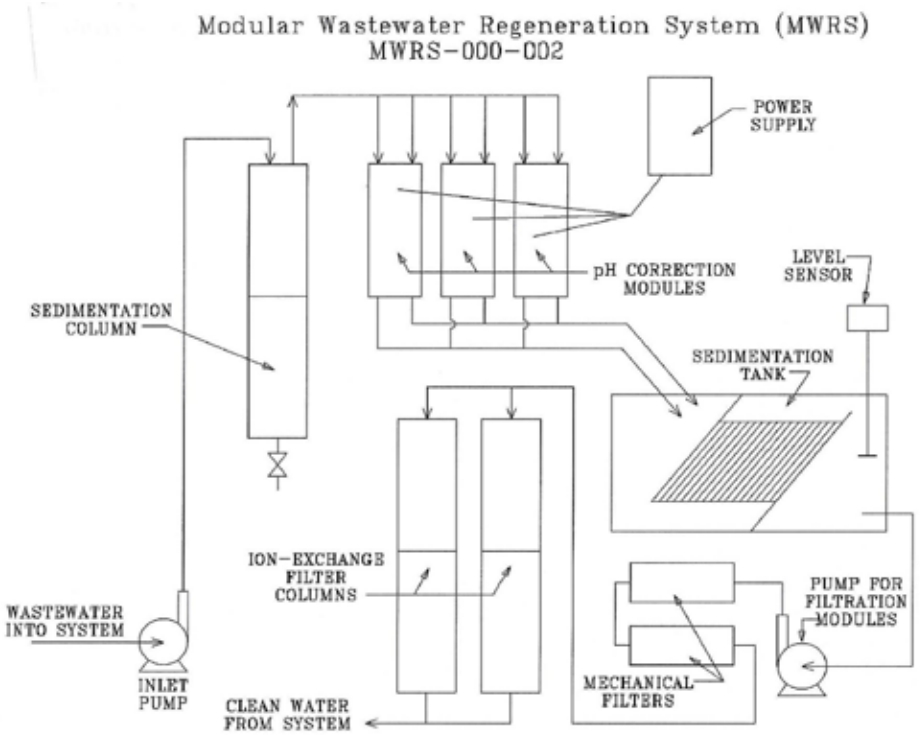


Figure 4. *Compact Modular System Configuration Without Intermediate Technological or Structural Components*



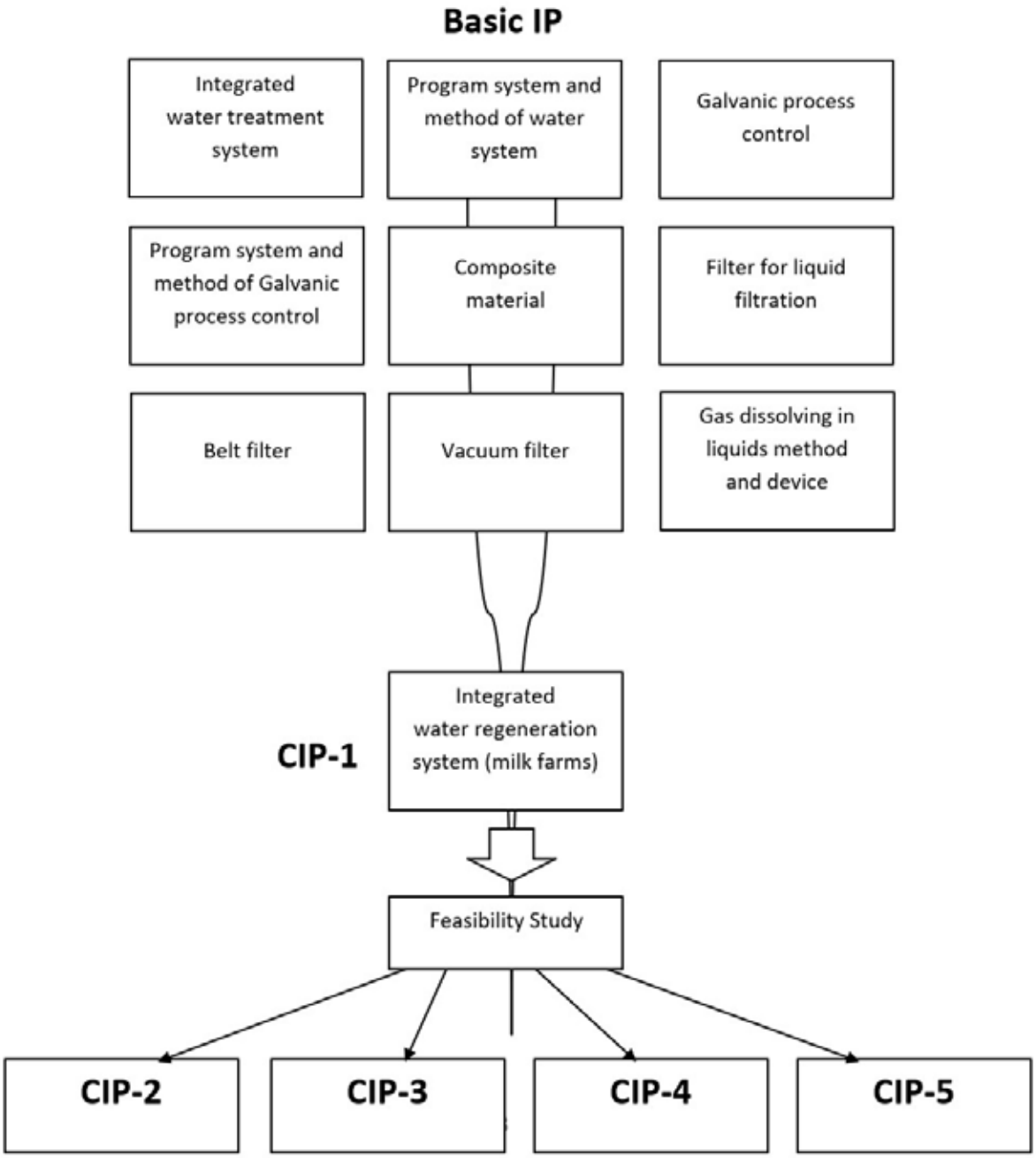
As demonstrated by the figures and diagrams presented above, the hierarchical architecture of vertically integrated modular systems enables the simultaneous resolution of technological and environmental challenges while satisfying the operational requirements of industrial facilities of various types and processing capacities, regardless of the degree of contamination of their industrial waste streams, through their complete regeneration and subsequent recirculation. Furthermore, this modular engineering approach facilitates the gradual transformation of manufacturing facilities with varying levels of operational complexity and organizational flexibility into so-called intelligent manufacturing systems (smart manufacturing facilities), characterized by advanced process automation, environmental sustainability, and integrated technological management.

As illustrated by the presented algorithmic diagram, which has also been developed taking into account the innovative concepts and engineering proposals derived from the inventions and scientific publications of Viktor-Vlad Ostap, a total of fourteen functional entities are represented. Each of these entities constitutes an integrated assembly of technological modules, themselves composed of autonomous modules belonging to lower combinatorial hierarchy levels.

Each of the presented modules constitutes an independent subject of patent protection, while every possible combination of these modules likewise represents a patentable technological solution and a legitimate subject for further continuation patent applications in accordance with the applicable patent legislation of the United States.

At present, industries utilizing water treatment technologies face numerous challenges that prevent auxiliary water treatment operations from achieving the same level of efficiency as the principal technological processes. The most significant challenges include:

- the continuous reduction in available water resources suitable for industrial process applications;
- the progressive deterioration of the quality of natural water resources available for technological use;
- the steadily increasing cost of industrial water resources;
- increasingly stringent environmental regulations governing the quality of wastewater discharged into municipal sewage systems, resulting in higher wastewater treatment costs;



- continuously increasing quality requirements for process water utilized in industrial production;
- the ongoing introduction of new synthetic, composite, and organic materials accompanying the development of advanced manufacturing technologies, requiring continuous modernization of water treatment facilities or the development of treatment systems possessing an exceptionally broad operational range, thereby substantially increasing both equipment costs and the overall cost of water treatment processes;
- the existence of numerous industrial facilities operating with conventional technologies whose water treatment equipment has reached the end of its service life, while replacement is either economically prohibitive or technically impractical.

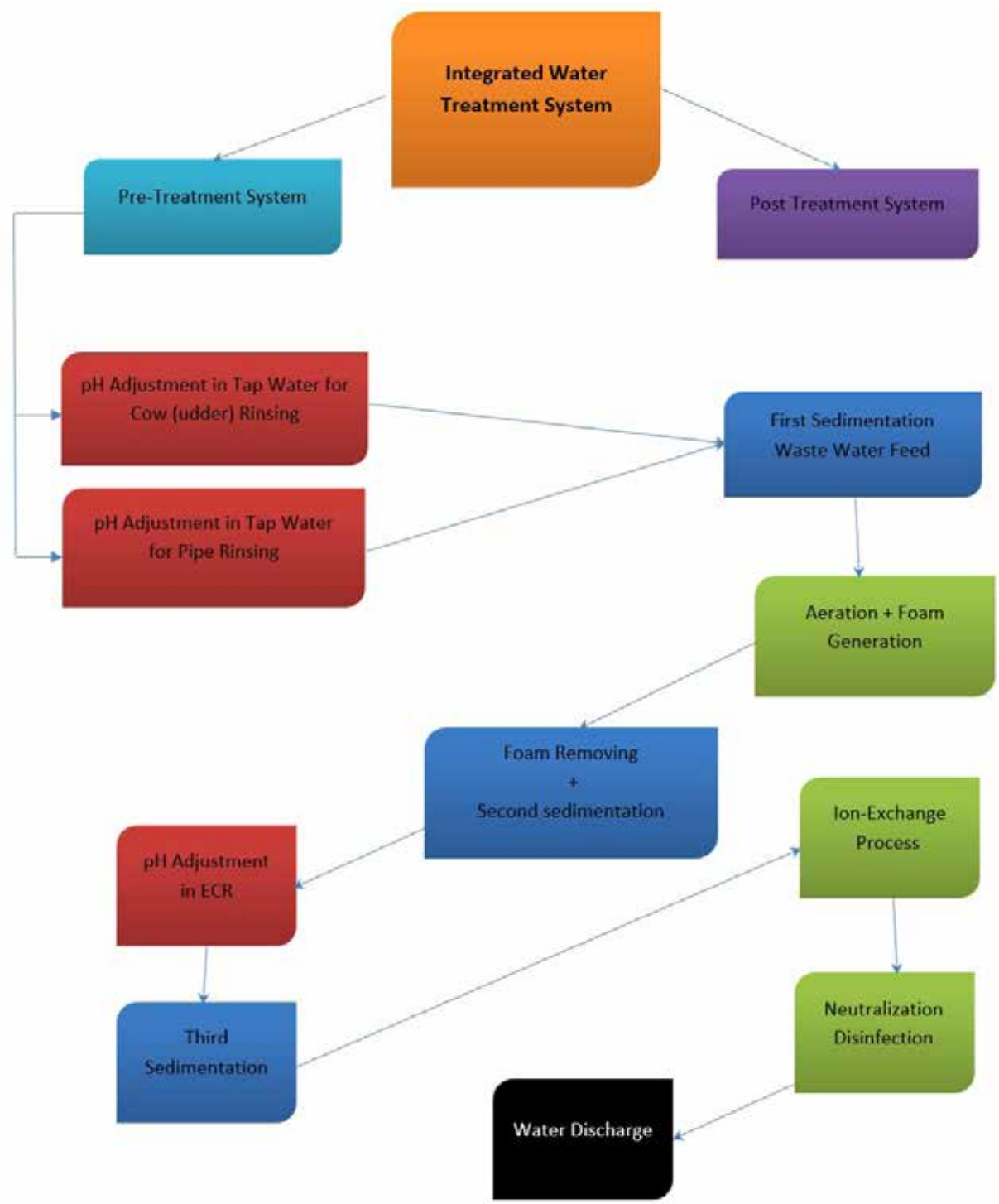
Patent and Licensing Status of the Proposed Technologies and Patentability of the Proposed Technological Methods

Based on preliminary engineering analysis and patent searches, the following sub-

jects have been identified for future patent applications:

- an integrated modular system for advanced treatment of water and aqueous solutions, together with its associated method of use;
- a comprehensive method for the treatment of water and the technological modules implementing the proposed method;

Integrated water treatment technology



- a method for the electrolytic extraction of metals from flowing water or aqueous solutions and electrode cells for implementing the method;

- a method for the aerodynamic foaming of water in a continuously flowing stream together with a foam generator for implementing the method;
- an integrated filtration method combining mechanical filtration, ion-exchange treatment, and biosorption;
- an electrocoagulation electrode cell incorporating coaxial electrodes;
- an electrocoagulation electrode cell incorporating a continuously moving belt cathode;
- an electrochemical cell for pH adjustment utilizing assemblies of polarizable soluble electrodes;
- an electrochemical cell for pH adjustment utilizing three-dimensional porous electrodes;
- an electrochemical cell for pH adjustment utilizing continuously moving belt electrodes;
- an electrochemical disinfection cell together with associated electrode assemblies for implementing the proposed disinfection method.

For each proposed patent application, prototype technologies and analogous engineering solutions have been identified from among the innovative developments and inventions of *Ostap Victor Vlad*, the originator and principal developer of the proposed technological concepts. Based on the results of the preliminary patent search and structural patentability analysis, the above-listed technical solutions have been determined to possess full patentability.

Building upon the foregoing concepts, and in combination with the proposed vertically integrated modular architecture, it becomes possible to establish the block diagram of an integrated technological complex in which the flexibility and selectivity of each technological process are achieved at the level of every individual module belonging to the lowest tier of the hierarchical modular structure.

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