Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-44992
www.engineeringscience.rs

iipp publishing

Journal of Applied Engineering Science
Vol. 22, No. 3, 2024
Original Scientific Paper
Paper number: 22(2024)3, 1217, 527-536

INTELLIGENT RADIOACTIVE WASTE INACTIVATION AUTOMATION SYSTEM

Apostolos Tsagaris*, Margarita Taousani, Georgios Mylonas

International Hellenic University, School of engineering, Department of Industrial Engineering and Management, Thessaloniki, Greece

* *tsagaris@ihu.gr*

The paper deals with the implementation of an intelligent automation system that ensures the smooth operation of a radioactive waste inactivation system as well as the SCADA system responsible for monitoring the entire automation system. It includes the inspection of five radioactive waste management tanks and a central radioactive waste collection pit of a Nuclear Medicine laboratory. The purpose was to create an intelligent automation system with PLC with the possibility of the future expansion of the reservoirs after an increase in hospitalized patients. Object-oriented programming was used with modern control code development techniques, but also visualization of all necessary information. The states tested for system operation are Collection, Treatment, and Wastewater Waiting. Each of the 5 collection tanks has a level sensor, safety float, sewage agitation system, sewage inlet and outlet valves, wash valve, and sampling valve. The system has a central valve that directs wastewater from patient rooms receiving radioactive iodine treatment either to the quench tank system via a central sump or to the central sewer system. Active sewage is collected in the central well and pumped to the collection tank. The central well has a level sensor to activate the pumps and a safety float.

Keywords: radioactive waste management, SCADA, PLC, control

1 INTRODUCTION

The need for waste management was created almost simultaneously with the creation of the first human settlements in antiquity. Simply depositing on the soil surface and decomposing through natural cycles was not enough, as it resulted in the spread of disease and epidemics. The waste of a culture is a sample from which very useful conclusions can be drawn. Dietary habits, use of pharmaceuticals, hygiene habits, and more, are extracted by studying the waste of culture, being a reliable source of information. The advent of the 20th century brought a revolution in waste management and environmental science. Scientific research and social awakening, around issues of pollution and contamination along with the interest of governments, brought a mood to increase the control against unfettered pollution. A deeper understanding of pollution combined with the 3rd industrial revolution, which introduced the computer, electronic devices, microprocessors, and advanced telecommunications, redefined the operation of basic processes, including waste management.

Most of the technologies used today in the field of waste management are advanced versions of technologies created during the 3rd industrial revolution [1].

Technological enrichment is also responsible for the separation of processing from waste management as functional concepts. Over the years and with the advancement of technology and science, management and treatment have become distinct concepts in the field of waste. Treatment aims to clean, minimize pollutant load and remove contaminants from whatever is considered waste. Management aims at organization and control, both in the prevention of waste production, as well as in transport (network), storage, measurements, processing, legislation, and finally disposal or other use. Sources of production can be urban, industrial, surface, and stormwater. One of the main sources of waste production is the volume of hospital waste and especially radioactive waste produced in Nuclear Medicine departments. Most of the radioactive waste is liquid, with a smaller amount of solids and very little gas.

The safe disposal of radioactive materials and objects contaminated with them is a vital component of the overall hospital waste management strategy. The fundamental purpose of the safe disposal of radioactive waste is to ensure that radiation exposure in public places and the environment does not exceed the prescribed safe limits. The management of radioactive waste is called upon to become faster, more efficient, energy-friendly, environmentally friendly, and legally updated over time [2]. The main resource available to humanity for the realization of these is technology. The development of which is full of benefits, if it is used rationally. The new technologies and new trends that have emerged and are evolving and being implemented experimentally or in reduced and trial use are many. The one that stars, essentially being the smart solution to waste management in many cases, is the use of programmable logic controller PLC and SCADA systems integrating all the modern aspects of the 4th industrial revolution.

2 STATE OF THE ART

According to study [5], a solution is proposed to simplify the sample collection and measurement procedures before the discharge of radioactive wastewater into the public environment. Specific activity measurements for radioactive wastewater drainage can be performed using a relatively inexpensive NaI(Tl) crystal detector without relying on an expensive HPGe high-purity germanium detector or a gamma Ray counter. When measuring radioactivity using a NaI(Tl) crystal scintillation detector with a diameter of 38 mm and a height of 38 mm, which is the smallest commercially available detector, the minimum detectable activity (MDA) was found to be less than that of drainage standard for radioactive waste provided by law. The system can be improved by using a larger scintillation detector, the measurement time can be extended to several hours or days, and it can be used for wastewater with a long half-life [5].

Because no cost-effective and efficient radioactive waste removal technologies are available, currently, radioactively contaminated hospital wastewater must be stored until the contained radionuclides have sufficiently decayed [6]. This study focuses on the use of hybrid membranes that effectively remove heavy metal ions and radioactive compounds from water. Hybrid membranes composed of amyloid fibrils produced from inexpensive and readily available proteins and activated carbon are highly effective in adsorbing and removing a variety of clinically relevant radioactive compounds from hospital wastewater by one-step filtration. Technetium (Tc-99m), iodine (I-123), and gallium (Ga-68) radionuclides can be removed from water with over 99.8% efficiency in a single step. The approach presented here is scalable, sustainable, and very low-cost, as it relies on very affordable raw materials. Importantly, the membranes have been shown to have the potential to be used to clean up radioactive wastewater on a large scale. By converting large volumes of radioactive wastewater into low volumes of solid radioactive waste, the present technology is emerging as a potential game changer in nuclear wastewater treatment [6].

In study [7] is reported for first time that osmosis can be successfully used to concentrate radioactive liquid waste produced by radiotherapy in hospitals. Osmosis was initially evaluated for the treatment of natural and radioactive iodine (125I) under different pH and different solvents to obtain optimal operating conditions. The performance of osmosis during the treatment of real radioactive wastewater containing iodine 131I was investigated in terms of water flux and rejection rate resulting in osmosis removing iodine up to 99.85%, observed as a significant reduction in flux due to contamination of the membrane by organic and inorganic substances. As a result, osmosis can effectively reduce the volume of the septic tank, allowing an increase in the number of radiotherapy rooms (eg from 2 rooms to 8 rooms at a rate of 75%. recovery rate) [7].

Targeting current biosafety management problems in nucleic acid laboratories, the work of wansha et al. designs and builds an intelligent laboratory biosafety management system to realize intelligent supervision and computerization of laboratory biosafety management data. The intelligent laboratory biosafety management system solves two key tasks of laboratory biosafety management, namely, laboratory biosafety oversight and biosafety risk assessment. The system architecture adopts the Internet of Things-based smart lab model to design and consists of the perception layer, the network layer, and the application layer. Among them, laboratory biosafety risk assessment research is an important content of building an intelligent biosafety system in the nucleic acid testing laboratory, and creating a biosafety risk assessment model is the key task [8].

Very important is the effective design of the SCADA in radioactive waste management systems. Nemcik et all [10] presents the design and implementation of a modern distributed control SCADA system. The control includes rail vehicles for the transport and storage of waste. The control and strategy for coupling/uncoupling and movement of connected vehicles is described. The control system is implemented in a programmable logic controller, which is widely used in industrial application. In Samudro M., & Setiawan A. [11] work they present an automated carrier-free Lu-177 radiochemical extraction system from the ytterbium target, fully controlled by programmable controllers. Its architecture is based on three levels and uses the Scada system, combined with an OPC server database. The OPC server is used to collect data from Modbus TCP and Modbus RTU protocols as well as upgraded fieldbus data exchange protocols.

2.1 General principles of radioactive elements

The fields of nuclear medicine and pharmaceuticals [3], in the last twenty years, have experienced a leap forward in development. The progress of technology, computers, detectors, and radiopharmaceuticals also contributed to this fact. By nuclear medicine, we mean that branch of medicine that uses radiation and the nuclear properties of stable and radioactive atoms for diagnostic-therapeutic purposes. It refers to the radiation to which the patient is subjected through the use of an external source, or radioactivity from the administration of radioactively labeled drugs - radiopharmaceuticals. The exposure of these patients to radiation is justified by the fact that the very important information obtained by nuclear medicine techniques would not be possible to obtain in any other way.

Radiation limits in this medical practice do not exist, while the weighting between expected benefit and threatened risk is decided on a case-by-case basis jointly by the doctor and the patient. All nuclear medicine techniques aim at diagnosis or treatment. The radiation comes either from an external source (high-energy electron source or γ-radiation source) or from an internal source (administration of radiopharmaceuticals).

The administered radiopharmaceutical should remain in the specific organ of the body for the minimum period to fulfill its purpose. The effective time for a radiopharmaceutical depends on both its biological and physical half-life. Biological half-life is defined as the length of time a drug remains in the body before being inactivated through metabolic processes or excreted. Since the natural doubling times of the radionuclides used in nuclear medicine are known, what is studied by nuclear medicine is the biological behavior of the tracer in the body. Another very important factor is the type of radiation emitted. The choice of the specific radionuclide is determined by the type of radiation it emits. In diagnostic situations, the purpose of radiopharmaceuticals is to image biological structures. To achieve this imaging, radiation that is sufficiently penetrating is required, so that after first penetrating the patient, it reaches the detector interacting as little as possible with his tissues, to minimize the dose that is ultimately absorbed. For this reason, the preferred radionuclides are those that emit only γ- or -X-radiation, without particle radiation. Such are the radionuclides that decay by electron capture or isomeric transition.

Radionuclides used for imaging have different characteristics than those used for treatment. Radiotherapy aims to destroy the affected tissue, which is achieved by ionization and the production of free radicals from the radiation. Thus, radiations of high specific ionization and short, well-defined range are preferred because they cause local tissue destruction in a small but specific area. More suitable radionuclides for therapeutic purposes are those that emit α-radiation, low-energy β-radiation, or Auger electrons.

2.2 The half-life of radioactive elements

The rate of decay of a radioactive element is expressed through the doubling time, or half-life, ($t_{1/2}$), defined as "the time required for half of the original amount of radioactive material to decay" [3], It expresses the stability of a radioactive substance, as the higher its value, the more stable its nucleus. Radioactive waste, like any radioactive material, decays based on the half-life of each isotope it contains. Each isotope has its characteristic half-life, which can be from very short, e.g. 12 seconds for barium (^{143}Ba), to very long, e.g. 4.5 billion years for uranium (^{238}U). Thus, some radioactive waste - never "dies" and requires long-term and careful management in special units, while for some others - short-lived - a simple, on-site management is sufficient.

A radioisotope used for diagnosis must emit rays of sufficient energy to be emitted by the body and must have a half-life short enough to decay soon after imaging is complete. The radioisotope most widely used in medicine is Tc-99, which is used in about 80% of all nuclear medicine procedures. It is an isotope of technetium that is artificially produced and has almost ideal characteristics for a nuclear medicine scan, such as with SPECT.

These are [4]:

- It has a half-life of six hours, which is long enough to examine metabolic processes, but short enough to minimize the radiation dose to the patient.
- Decays by an "isomeric" process, which involves the emission of γ-rays and low-energy electrons. Since there is no high-energy β emission, the radiation dose to the patient is low. The low-energy γ-rays it emits easily escape the human body and are accurately detected by a γ-camera.
- The chemistry of the technetium is so versatile that it can form tracers by incorporating a range of biologically active substances that ensure it concentrates in the tissue or organ of interest.

2.3 Pharmaceutical forms of radionuclides

The main forms of medical radionuclides are summarized below:

- Radionuclides produced in the reactor.
- Radionuclides produced in the cyclotron present significant advantages over those produced in the reactor. It is short-lived and therefore the dose received by the patient is significantly reduced.

2.4 Segregation of radiopharmaceuticals as radioactive waste

Over 40 million nuclear medicine procedures are performed each year worldwide, and the demand for radioisotopes is increasing by up to 5% per year. Sterilization of medical equipment is also an important use of radioisotopes. About one person in 50 uses a diagnostic radiopharmaceutical each year. About 50% of hospitals use radioisotopes in medicine and about 90% of cases are for diagnosis.

Radioactive medical waste is only produced in nuclear medicine laboratories where it exists. When we say radioactive residue-waste, we mean: "any material that has been contaminated or contains one or more radioisotopes, whose value of emitted radioactivity is not negligible and which are certainly not intended to be used further" [2].

Radioactive waste is classified, in order of increasing risk, into:

- Very Short Level Waste, VSLW
- Very Low-Level Waste, VLLW
- Low-Level Waste, LLW
- Intermediate Level Waste, ILW
- High LevelWaste, HLW

2.5 Nuclear medicine laboratory

The system described manages waste from the collection of radioactive excreta through the appropriate tanks and pits. The tanks have a maximum capacity of 7000 each. This size of tanks was determined after market research and for practical reasons of transportation and installation. Each tank will have a capacity of 95% of its maximum volume, i.e. a final maximum capacity of 6650 lt.

Based on patient movement data over the last 5 years, the number of patients hospitalized with thyroid cancer does not exceed 75 per year, for this specific application. For the calculations, it is assumed that 90 patients per year are treated with I-131 in both chambers.

Each patient is hospitalized for 7 days, therefore: 90 days/year x 7 days/year = 630 days/year.

On average each patient uses the toilet 7 times and each time 10 lt of water is consumed and a total of 2 lt of urine and feces are excreted, that is approximately 75 lt of wastewater from each patient. The average daily volume of wastewater for 630 days of hospitalization per year is calculated at 129 lt/day:

(75 lt/day x 630 days/year)/365 days/year = 129 lt/day

It is calculated based on the capacity of each tank and the average daily volume of sewage as follows:

6650 lt / 129lt/day = 51.5 days. Therefore, the described tank is filled in 51.5 days.

2.6 Average daily discharged radioactivity

To calculate the average annual administered radioactivity:

- The average annual administered radioactivity is initially calculated. From data on the movement of patients in the department over the last 5 years, the average administered radioactivity per patient with thyroid cancer does not exceed 120mCi/patient. I-131.
- Therefore: 90 mCi/year x120 mCi/m. = 10800 mCi/year.
- Then the average annual emitted radioactivity is calculated. From measurements and literature data, it is assumed that 90% of the administered radioactivity is excreted by the patient into the sewage system.
- Therefore: 10800 mCi/years 90% = 9720 mCi/year.
- The average daily emitted radioactivity is:
- (9720 mCi/year) / (365 days/year) = 26.6 mCi/day.

2.7 Average concentration of radioactivity in the tank on the day of filling

The total radioactivity A of the tank at the end of its filling time is calculated assuming that each day has an enrichment of radioactivity by Ao=26.6 mCi/day and a simultaneous decrease in radioactivity due to radioactive decay. So the total radioactivity is expressed in the following order:

$$A = Ao\, e^{-\lambda\tau}{}_1 + Ao\, e^{-\lambda\tau}{}_2 + Ao\, e^{-\lambda\tau}{}_3 + \ldots + Ao\, e^{-\lambda\tau}$$

which is transformed into an integral with limits t=0 to t= 51.5 days.

$$A = \int_0^t Ao\, e^{-\lambda\tau} dt = Ao\, [(-1/\lambda)\, e^{-\lambda\tau} + c]$$

For t=0 A=0 c=1/λ is calculated where λ: the decay constant of **I**-^{131} is equal to 0.087 dm^{-1}.

Therefore:

$$A = Ao\, [(-1/\lambda)\, e^{-\lambda\tau} + 1/\lambda\} = (Ao/\lambda)\, (1 - e^{-\lambda\tau}) = \mathbf{302\ mCi}$$

The maximum radioactive concentration of the tank at the end of its filling time is calculated by dividing the maximum radioactivity by the filling volume of the tank.

$302\ mCi / 6650\ lt = \mathbf{0.045\ \mu Ci/ml = 4.5 \times 10^{-2} \mu Ci/ml}$

2.8 Residence time of wastewater in the tank

Wastewater collected in the tank must remain in the tank for a certain period of time for the radioactive concentration to drop to the desired 10^{-5}μCi/ml, at which point it can be discharged into the public sewer system. The isolation period of the tank is calculated from the radioactive decay equation.

$$C = Co\, e^{-\lambda\tau} t = (InC - InCo)/\lambda = \mathbf{90\ days}$$

2.9 Calculation of the number of tanks

The number of tanks, with a volume of 7000 lt each, is calculated depending on the time of filling the tank and the time of isolation of the tank.

$$N = (96.5 + 51.5) / 51.5 = 2.9 \quad \text{3 Tanks}$$

3 ARCHITECTURE OF RADIOACTIVE WASTE INACTIVATION AUTOMATION SYSTEM

Taking into account the above radiation protection study for the automation and control requirements of the radioactive waste reduction tanks, an automatic system with PLC [9] was created with the possibility of the future expansion of the tanks from 3 to 5 tanks due to the continued increase of hospitalized patients.

The System_Tank programming object with all its inputs and outputs, Fig. 1.

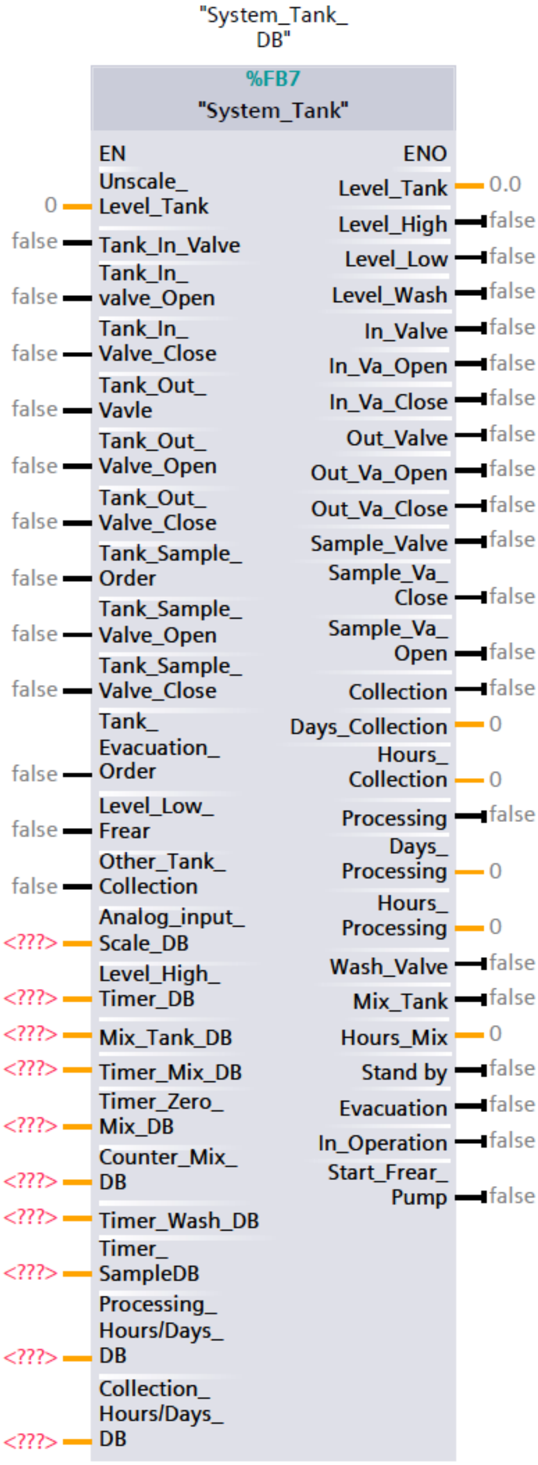


Fig. 1. System_Tank programming object

The Evacuation process is shown in the diagram below (Fig. 2) and is activated when the Evacuation inlet empties and flushes the tank. After the end of the wash time and if the tank level drops below 10% the outlet valve closes and the tank goes into STANDBY mode.

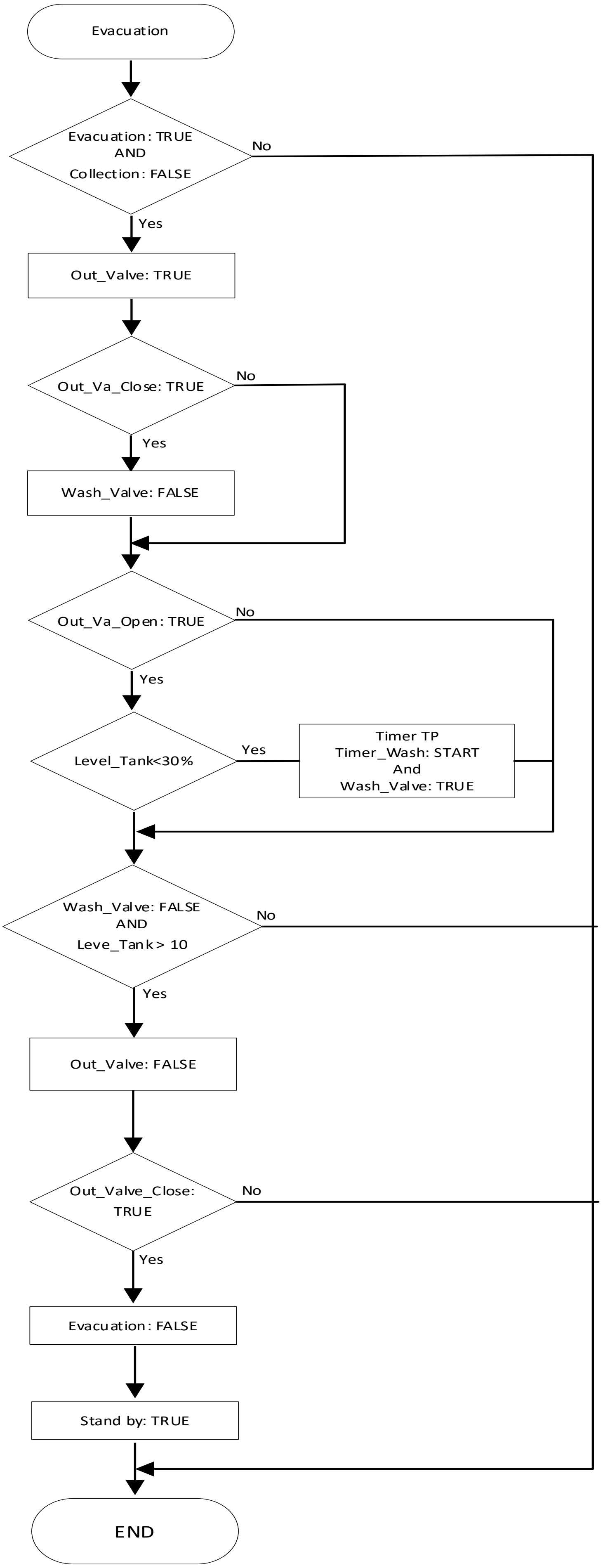


Fig. 2. Evacuation Program Flow Chart that empties and flushes the tank

In all situations, the sampling process can be activated which opens the sample valve for a specified time. The flow chart below shows the operating procedures of the tank, Fig. 3.

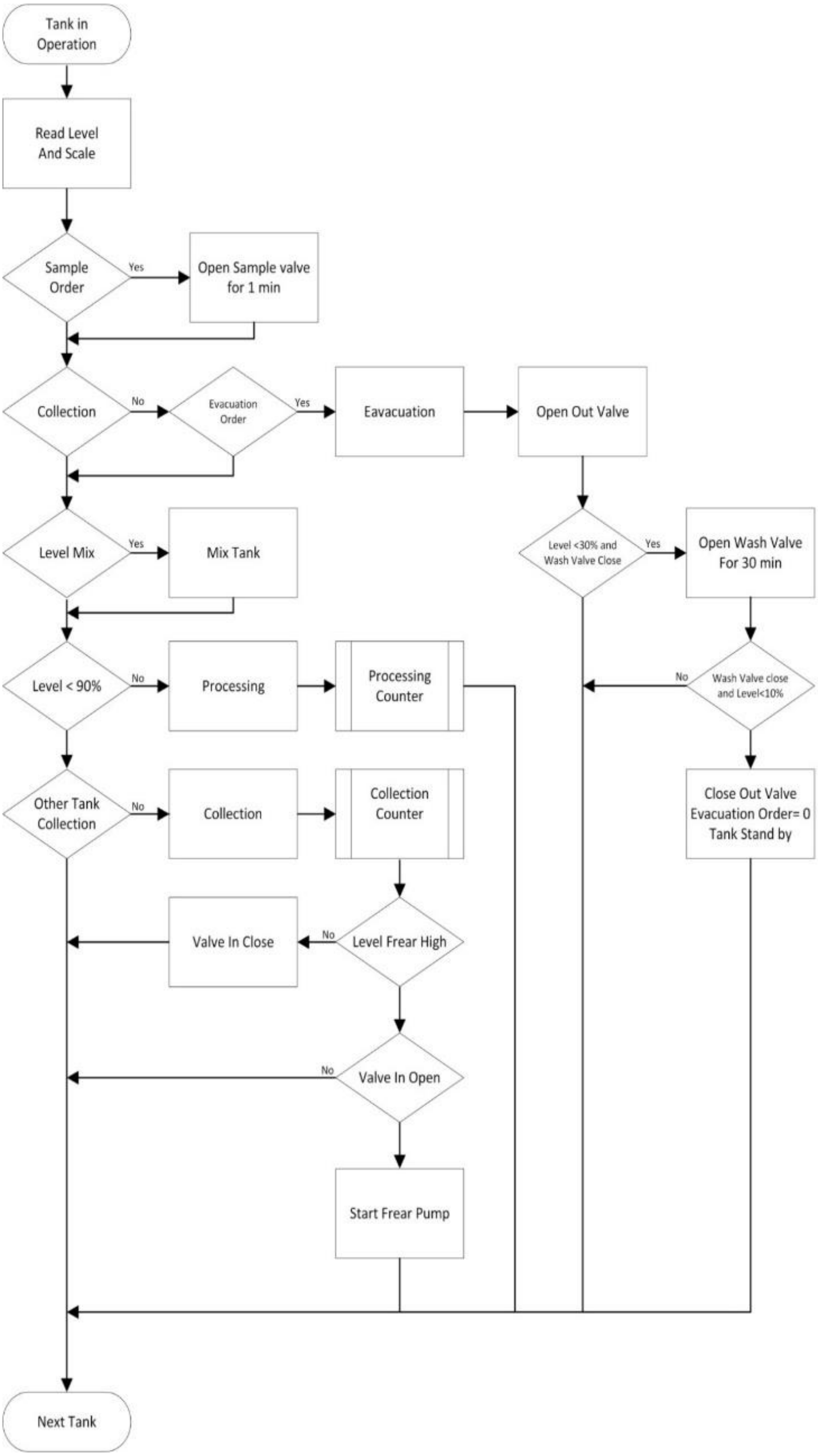


Fig. 3. Tank Operation Process Flow Chart

4 SYSTEM SIMULATION

The Screen_Tank screen is the control and monitoring screen of the system, while the Screen_Trend screen records the level of the tanks.

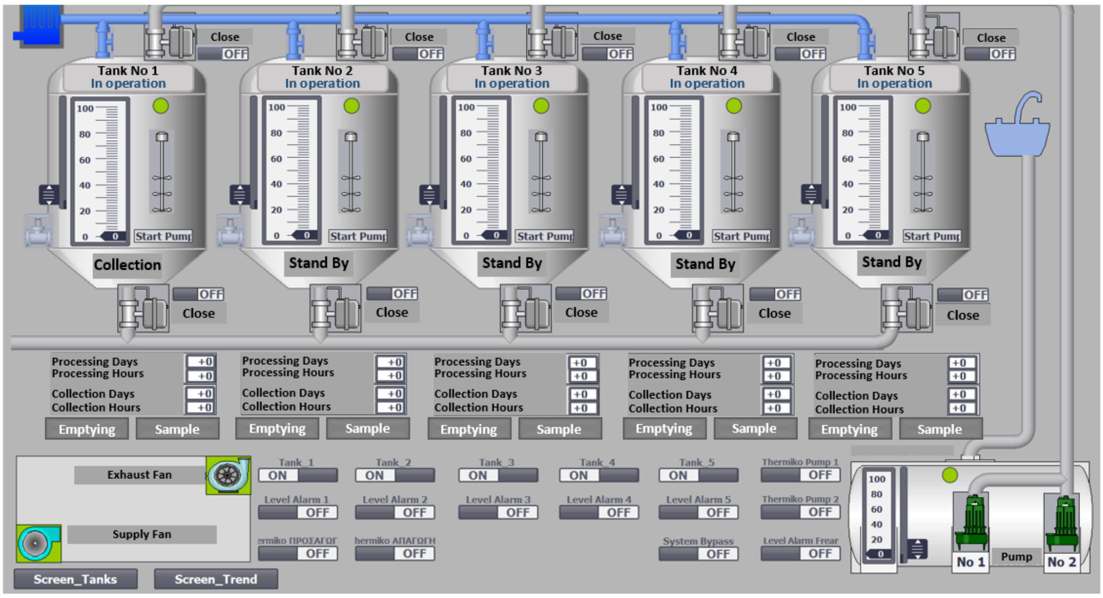


Fig. 4 Screen_Tank Screen – Tank & Central Well System

The screen named Screen_Tank is about the overview of the installation with the five tanks and the central sump and generally how all the components are connected. In more detail, this screen contains the entire function of the automation of the thesis consisting of 5 radioactive material storage tanks, 2 pumps in the central well, 1 inlet valve, 1 outlet valve, 1 sampling valve, and 1 washing valve in each tank, 1 agitator for each tank and 2 exhaust and supply fans, Fig. 4.

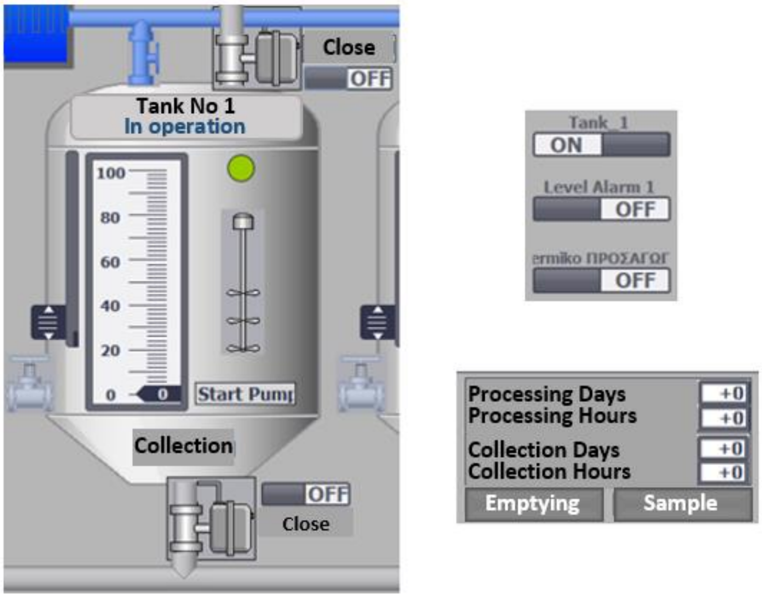


Fig. 5. Screen_Tank-Tank No1 and function switches

At the top of each tank is an indication (blue letters) of whether it is ON or OFF and at the bottom, if the tank is COLLECTING, PROCESSING, WAITING, OR EMPTYING. Each tank has an inlet and outlet valve with indications of whether it is closed or open. The slide switch next to the valve can set the valve to a closed or open position for simulation purposes and when the valve is commanded to open it flashes on a green background, Figure 6.

In the middle of each tank, there is a level indicator and a sliding bar to simulate it. It has an independent high-level sensor (circular indicator) which is green when the level is at a normal level and turns red when the level exceeds the permissible limit. There is a stirrer with an indicator when the tank is stirred and the Start Pump indicator, which is activated by the start command of the central well pump (Fig. 5).

At the bottom of each tank are the counters for the days and hours of collection and processing, below the counters are buttons for emptying the tank and taking a sample. Also, there is the Tank_1 slider for manipulating the tank and the simulation button for the LevelAlarm 1 level sensor.

When the sewage is led to the entrance of the central well above the well there is an indication SYSTEM IN COLLECTION. Otherwise, the wastewater through the pipes of the sink is connected to the central drain and the system is marked SYSTEM IN BYPASS.

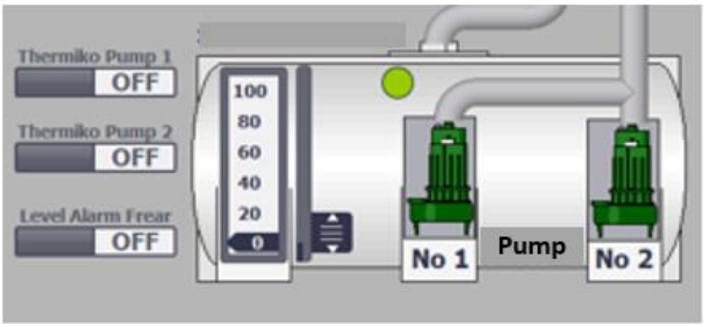


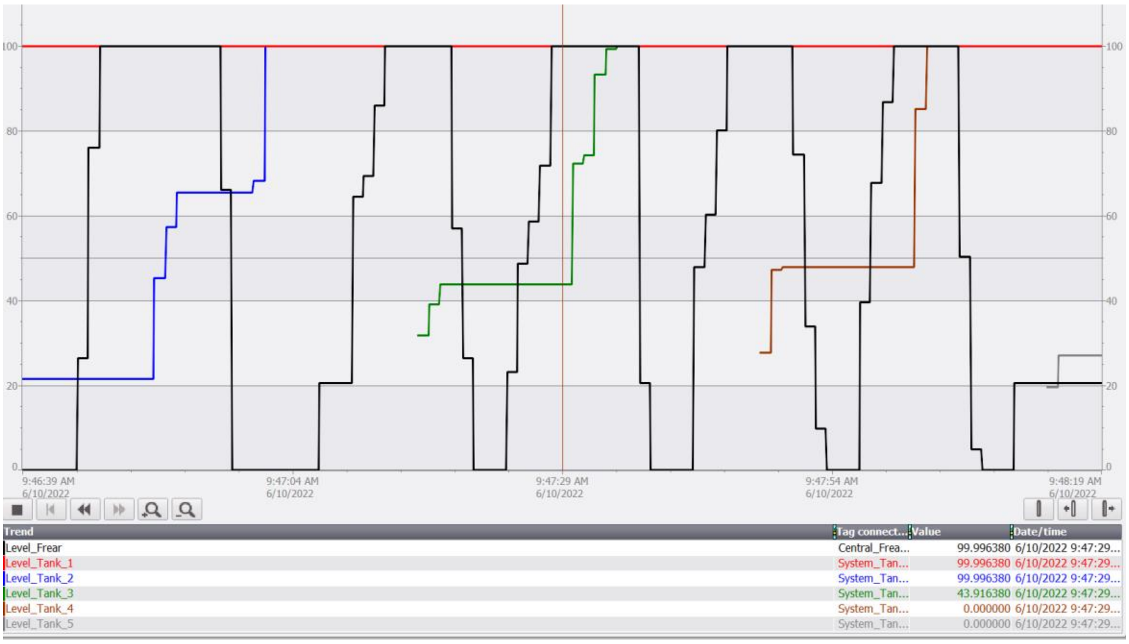
Fig. 6. Screen_Tank-Center Tank screen and power switches

In the center well there is a level indicator and slide bar to simulate it with a high-level indicator which is green when the level is at a normal level. There are slide buttons to select Thermiko Pump 1, Thermiko Pump 2, and a button for the LevelAlarm Frear level sensor for simulation, Fig. 6.

Fig. 7. Screen_Tank- Gas Extraction and Supply System

Finally, in the lower left part of the screen, we have, indicatively for the operation of the air supply and exhaust fans, and corresponding switches for handling the thermals, Fig. 7.

In the Screen_Trend screen, we have the graph of the tank level variation. As can be seen in the image, the level of the central well is shown with the black characteristic curve, while the levels of the tanks (1-5) the red, blue, green, brown, and gray respectively, Fig. 8.



Trend	Tag connect...	Value	Date/time
Level_Frear	Central_Frea...	99.996380	6/10/2022 9:47:29...
Level_Tank_1	System_Tan...	99.996380	6/10/2022 9:47:29...
Level_Tank_2	System_Tan...	99.996380	6/10/2022 9:47:29...
Level_Tank_3	System_Tan...	43.916380	6/10/2022 9:47:29...
Level_Tank_4	System_Tan...	0.000000	6/10/2022 9:47:29...
Level_Tank_5	System_Tan...	0.000000	6/10/2022 9:47:29...

Fig. 8. Screen_Trend – Graphical Representation of tank level

5 CONCLUSIONS

The understanding of the importance of the proper management of radioactive waste in the modern era, both by those involved in the health sector and by the administration and citizens, is an imperative issue, as in recent years the management of environmental quality has been approached with anxiety and as it follows that the use of technology is an integral part of achieving this goal.

Below are the conclusions reached after the study and implementation of the radioactive waste inactivation tank system, as well as the improvements that will occur soon with the development of the relevant technologies. A PLC unit with the corresponding SCADA interface was selected for the implementation of the system. The shared database between PLC and HMI was what increased the functionality of the application. It is worth noting that with the use of this specific programming platform, there was no need to use any other utility operating program for the successful operation of this system.

It is interesting to mention that the choice to create a System Tank programming object for all tank operational states enabled the system to be easily extensible. Because currently radioactively contaminated hospital wastewater must be stored until the radionuclides have decayed sufficiently and no cost-effective and efficient removal technologies are available, the scalability of the radioactive wastewater management system is a primary objective nowadays with the continued increase in patients undergoing the use of radiopharmaceuticals.

After simulation, it was shown that all the designed requirements were performed for a five-tank system in both normal and emergency operating conditions with the ability to record all events for investigation and evaluation over time.

In the future, the interest could turn to research on systems for filtering and reducing the volume of radioactive waste using special membranes and in combination with the tank inactivation system could be a potential game changer in the treatment of radioactive wastewater.

6 REFERENCES

[1] Rifkin, J. (2011). *The Third Industrial Revolution*. Palgrave Macmillan.

[2] Margonis, C. (2018). *Management of Radioactive Waste in a Hospital Environment*. University of Patras.

[3] Arsos, G., Gotzamanis-Psarrakou, A., Karatsanis, K.G., & Karatzas, N.D. (2003). *Nuclear Medicine*. Ziti Publications.

[4] Anninos, F.A. (2010). *Medical Physics and Radiophysics*. Parisianou S.A.

[5] Sangrok, K., Taeyoon, K., & Hyungjin, Y. (2022). Design of a Low-Resolution Gamma-ray Spectrometer for Monitoring Radioactive Levels of Wastewater. *Applied Science*, 12(11), 5613. https://doi.org/10.3390/app12115613

[6] Bolisetty, S., Coray, N., Palika, A., Prenosil, G., & Mezzenga, R. (2020). Amyloid Hybrid Membranes for Removal of Clinical and Nuclear Radioactive Wastewater. *Environmental Science: Water Research & Technology*, 6(12), 3249-3254. https://doi.org/10.1039/D0EW00693A

[7] Lee, S., Kim, Y., Park, J., Shon, H.K., & Hong, S. (2018). Treatment of Medical Radioactive Liquid Waste Using Forward Osmosis (FO) Membrane Process. *Journal of Membrane Science*, 556, 238-247. https://doi.org/10.1016/j.memsci.2018.04.008

[8] Wansha, L., Kunning, S., & Jingzhe, L. (2021). Design and Research on the Construction of an Intelligent Biosafety Management System for Nucleic Acid Laboratories. *Electronic Journal of Emerging Infectious Diseases*, 6(4), 352-355.

[9] Petruzella, F.D. (2018). *Programmable Logic Controllers (5th ed.). Tziolas Publishing.*

[10] Nemcik, J., Krupa, F., Slanina, Z., Ozana, S., Koziorek, J., & Polak, D. (2020). Autonomous Distributed Control System Strategy of Rail Vehicle for Nuclear Waste Disposal. *Proceedings of the 20th International Conference on Control, Automation and Systems (ICCAS)*, Busan, Korea (South), 906-911. https://doi.org/10.23919/ICCAS50221.2020.9268242

[11] Samudro, M., & Setiawan, A. (2020). Study of the Use of the Internet of Things (IoT) on Ion Exchange Equipment as a Long-Term Control and Monitoring in the Processing of Liquid Radioactive Waste. In Sugianto (Ed.), *Proceedings of the 2019 Presentation Forum on Results and Activities of the Radioactive Waste Technology Center (PLTR) (pp. 288-294).* Jakarta, Indonesia: Center for Radioactive Waste Technology, National Nuclear Energy Agency.

Paper submitted: 13.06.2023.

Paper accepted: 07.08.2024.