APPLICATION OF RCM CONCEPTS IN RELIABILITY-BASED DESIGN OF CHEMICAL PROCESSING PLANT

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Abstract: *The development of complex chemical processing plant design based on reliability concepts aims at predicting the probability of occurrence of failures during the plant operational life. The plant pieces of equipment selection procedure based on reliability can be used to reduce the occurrence of critical failures that could affect not only the plant operation but also the personnel and environmental safety. The analysis also intends to develop a maintenance plan for those critical pieces of equipment aiming at reducing the frequency of failures in order to increase plant availability and operational safety. The most used tool as for maintenance planning aiming at attending those requirements is Reliability Centered Maintenance – RCM. This work shows the application of RCM concepts toward pilot project for Anhydrous Hydrofluoric Acid Tanking Unit at USEXA, located at the CTMSP plant. Using the RCM methodology, the analysis first step involves the delineation of the limits of the system, subsystems, items and components aiming at the definition of the functional relation of those components. In the next step the analysis of causes, effects, consequences and criticality of failures, also known as Failure Mode and Effect Analysis, is developed for each subsystem of the unit. Finally, for the critical equipment, selected based on the results FMEA analysis, a maintenance plan based on RCM concepts is proposed aiming at reduction of the risks associated with the processing of anhydrous hydrofluoric acid.*

Keywords: *Reliability centered maintenance. Failure mode and effect analysis - FMEA. Anhydrous hydrofluoric acid.*

1. INTRODUCTION

The "*Centro Tecnológico da Marinha em São Paulo* (CTMSP)" is a research center of the Brazilian Navy aiming at promoting the development nuclear technology called Navy's Nuclear Program (NNP).

The NNP promote the development of the mains steps of the nuclear fuel cycle including design areas, process validation in laboratory scale, set up of the demonstration and pilot plants, mechanical workshops capability and technical and operational training of the productive units.

The CTMSP already dominated some of the nuclear fuels cycle areas such as enrichment, reconvention, fuel and fuels elements manufacturing.

To complete the nuclear fuel cycle on CTMSP it is required to finish the Uranium Hexafluoride Unit (USEXA) which now is in electro-mechanical construction phase.

The proposition of the USEXA is to convert the uranium concentrated from the mine to fluoride compost known as uranium hexafluoride (UF_6) (USEC, 1999). On convertion process the uranium passes through several steps such as: dissolution, filtering, purifying, precipitation, calcination, hydrofluorination and finely by fluorination.

The route adopted in USEXA for obtaining UF_6 is divided in two stages. The first stage starts at the receiving of the raw material, pass through the yellow cake production, until obtaining the uranium trioxide (UO_3). The main inputs used in this stage are nitric acid, ammonium for precipitation reaction of ammonium diuranate (ADU) with nuclear purity in aqueous phase and posterior filtering. The first stage that involves chemical reactions in aqueous phase is denominated wet route.

The second stage begins with reduction of UO_3 to uranium dioxide (UO_2) by reaction with hydrogen arisen from ammonia cracking and posterior hydrofluorination of the UO_2 to uranium tetrafluoride (UF_4) in Continuous Bed Reactor also known with dry route. In dry route, the anhydrous fluoride acid (AHF) is the main reactant for the conversion of UO_2 to UF_4. The conversion is completed in the next stage in Flame Reactor where the UF_6 is produced through reaction between UF_4 and fluorine.

In this context, this works has objective to show a proposition of the implementation of Reliability Centered Maintenance ((RCM) as a pilot project to USEXA for Anhydrous Hydrofluoric Acid Chilled Tankage Unit (C10.49).

The scope of this works is to show the mains stages for production of UF6 including the C10.49 Unit and also the main physical and chemical proprieties of the AHF with its peculiarities in relation to tankage and risks the facilities, workers and environment.

In the literature review the evolution of maintenance is shown. The tools available for implementing a policy of maintenance are displayed with a comprehensive approach and implementation phases of the RCM (FOX et.al, 1994).

The RCM proposition to C10.49 Unit is detailed and the maintenance policy that will be adopted for each subsystem of the Tankage when in operation is presented.

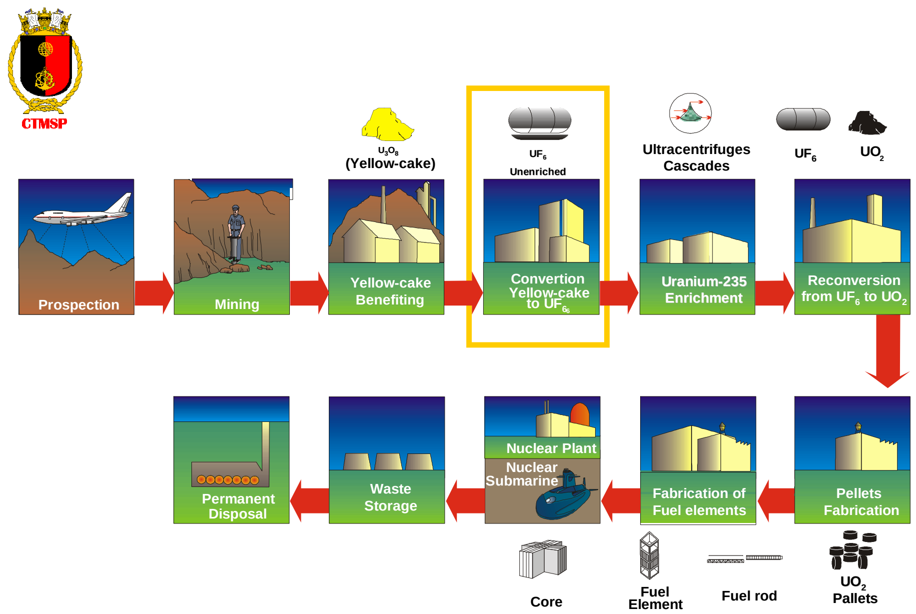
2. DESCRIPTION OF USEXA

Because of their physical and chemical proprieties the UF6 is compost very versatile. The UF_6 can be processed conveniently in three phases, solid, liquid and gaseous, in low pressure and low temperature environment.

The gaseous phase is used in the enrichment step, the UF_6 in liquid phase is used in transference step and solid phase is used for storage.

In according with, “The UF6 Manual Good Handling for Uranium Hexafluoride”(USEC, 1999), the triple point of the UF_6 occurs at 1.5 atm on temperature 64 ºC, therefore in this conditions of pressure and temperature the three phases coexist in equilibrium. With a very small raising temperature or pressure the UF_6 passes to liquid state or gaseous and reducing the temperature or pressure bellow the triple point the UF_6 change for solid phase.

The incidence of the uranium isotope 235 in nature is 0.735 %. For nuclear power reactors the degree of enrichment should be 4% and research reactors use uranium enriched to 20%. In the nuclear fuel cycle, the conversion stage has great importance because it produces UF_6 with purity suitable for the next step, the enrichment. The conversion is highlighted in Fig. 1 that shows the nuclear fuel cycle that goes from prospection to permanent disposal of wastes.



Source: Centro Tecnológico da Marinha de São Paulo

Figure 1. Nuclear fuel cycle

The USEXA, despite of uranium processing, is classified as chemical facility whose safety requisites and environmental integrity are very severe demanding operational and maintenance procedures well documented and quite comprehensive failure and operational databases.

The nominal capacity of the unit is 40 tons/year of the UF6 to attend the CTMSP necessities for the enrichment and construction of the first and second core of the pressurized water reactor "Pressure Water Reactor” prototype (PWR) for naval propulsion.

The CTMSP developed and coordinated projects and construction of the main equipments for USEXA on Brazilian industry. The nationalization of the projects and equipments were necessary due to barriers imposed by countries possessing the technology for conversion because the USEXA is strategic in nuclear area. Trade barriers required larger investments that cause delays in the schedule of works

The main operational steps of the USEXA are shown in Fig. 2.

The conversion is characterized by a relatively high number of operations. In flowchart, the production of UF_6 can be divided into two major groups in the presence of fluoride. The first group is fluorine-free production ranging from the dissolution of yellowcake to calcinations. The second group has the presence of fluorine ranging from the hydrofluorination to fluorination.

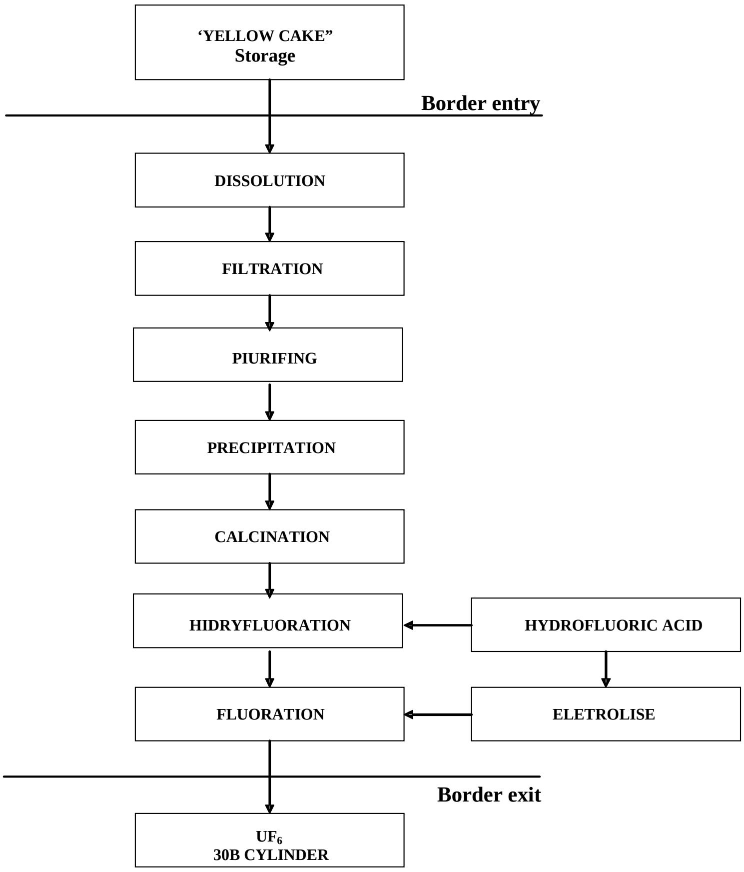


Figure 2. Flowchart of the conversion process

The production is in batches in USEXA, however, some steps may be carried out continuously, for example the step of purifying uranium, which is held in pulsed extraction columns.

Regarding the safety issue, the second process group, comprising the steps with the presence of fluorine is more sensitive because it uses as raw material the AHF, ammonium, hydrogen, elemental fluorine and uranium compounds. Another factor to be considered is the chemical reactions at temperatures above 350 °C in steps of the hydrofluorination fluorination.

The purpose of the C10-49 unit is to store the acid in below zero degrees Celsius temperature and its design is similar of the Nitroquímica company henceforth ex-producer of the acid.

The development of the RCM proposition for C10.49 Unit was executed considering only the basic design of the installations.

According to the Brazilian standard NR-13 - Boilers and Pressure Vessels published by Department of Labour and Employment of Brazil, (2006), the pressure vessels are classifieds in groups of the potential risk as function of result "PV", where "P" is the maximum pressure of operation, in MPa, and "V" is internal geometric volume, in m^3.

The storage facility of the hydrofluoric acid consists of three vertical tanks with capacity of 22 m^3 each. Each tank has a purpose: the first to receive the AHF, the second to distribute the acid to0 the plant and the third to receive the acid in case of emergency.

The maximum operation temperature is 19 ºC with pressure 0.002 MPa and according NR-13 standard, the storage vessel can be classified as Potential Risk Group 5 with "PV" less than 1.

The pressure vessel categories as function of Potential Risk Group and fluid grade are showed in Tab. 1.

The AHF is classified as Grade "A" - toxic with threshold limit value (TLV) ≤ 20 ppm and the vessel is classified as category III.

The three storage tanks are located within the containment tank of hydrofluoric acid whose humidity is controlled to minimize corrosion of the internal tanks. The content of three storage tanks is kept at - 8 ° C by a coolant fluid.

Dual containment arrangement, the inner tank and containment tank, provide a greater level of safety compared to conventional tanking systems.

The bay to receive the ISO tank is provided with sprinkler system in case of leakage. The acid is transferred from ISO tank, which may be at a temperature until 40 ° C, and passed through the heat exchanger before being transferred to the storage tank.

Table 1. Pressure vessels Category

CATEGORIES OF PRESSURE VESSELS

CLASSES OF FLUIDS	**1** **P.V ≥ 100**	**2** **P.V < 100** **P.V ≥ 30**	**3** **P.V < 30** **P.V ≥ 2.5**	**4** **P.V < 2.5** **P.V ≥ 1**	**5** **P.V < 1**
	Categories				
"A" - Flammable fluid and fuel with temp. at or above 200 ° C - Toxic with (TLV) ≤ 20 ppm - Hydrogen - Acetylene	**I**	**I**	**II**	**III**	**III**
"B" - Fuel with temperature less than 200 ºC - Toxic with (TLV) ≤ 20 ppm	**I**	**II**	**III**	**IV**	**IV**
"C" - Water vapor - Asphyxiating gases simple - Compressed air	**I**	**II**	**III**	**IV**	**V**

Source: Standard NR-13 obtained by Internet.

All tank connections are welded and exit pipes are designed considering the thermal expansion between fixing points of the inner tank and containment tank

Each tank is equipped with temperature monitoring instruments.

Pressure is another important parameter being controlled by the pressure transmitter in the storage tank. When pressure increases, the AHF is relieved to the scrubber or when the pressure in the tank is under vacuum, the instrument air is injected into the tank. The containment tank is a vertical cylinder and their main function is protecting the three internal tanks of AHF. The tank acts as a thermo insulate and a barrier in case of failure of one of the internal tank or failure of the piping system.

The access for inspection of the upper section of the internal tanks is through a hatch located next to an outside staircase of the containment tank. The inspection of the lower section of the internal tanks is executed through a stairway inside the containment tank.

The containment tank is provided with an automatic system of air dryer which purpose is to keep low humidity in order to prevent corrosion on the storage tanks, pipes and internal walls of the containment tank.

The main pieces of equipment that compose the tanking system are presented in Tab. 2.

Table 2. Roll of main equipments of the AHF tankage

Equipments
AHF Storage Tank AHF
AHF Cooler
AHF Containment Tank
AHF Containment Tank Dryer
Transfer AHF Pump
AHF Heather
Circulation AHF Pump

The tanking system of AHF in comparison with conventional tanking systems is endowed with extra equipments that operate primarily in assuring safety of the pump and heat exchanger aiming at keeping the temperature of the acid below zero degrees Celsius and thus keeping low pressure of acid.

3. APPLYING RCM CONCEPT FOR USEXA

The basic guidelines for the implementation of RCM are the same used by Electric Power Research Institute - EPRI and according to Willmeth at al (2000) are adopted seven key steps for implementing the method:

Establish the scope of the study where the boundaries are set to define the limits of work;

Identify the interfaces: the interfaces are identified to better define the limits of the study listing the inputs or connections that are not studied;

Specify the most important functions: RCM seeks to preserve only the most important functions of a system or equipment;

Identify dominant failure modes: the dominant failure modes for the important functions are identified for effect evaluation;

Identify critical failure modes using the FMEA analysis: the consequences of failure are evaluated for the dominant failure mode to determine their severity. The more serious the consequence the higher is the severity level, and the failure mode is considered critical. Non-critical failure modes are not considered in the study;

Identify the causes of failures using the FMEA analysis: the dominant causes of failure are identified only for failure modes considered critical.

Select the maintenance tasks: using the decision diagram for the selection of maintenance tasks. Maintenance tasks are selected considering the cost of failure and maintenance cost attributed to each cause of dominant failure. Changes in design and operation are also considered. Figure 3 shows the steps in the Logic Diagram of Decision considering the safety issue that is the main concern for USEXA maintenance plan development.

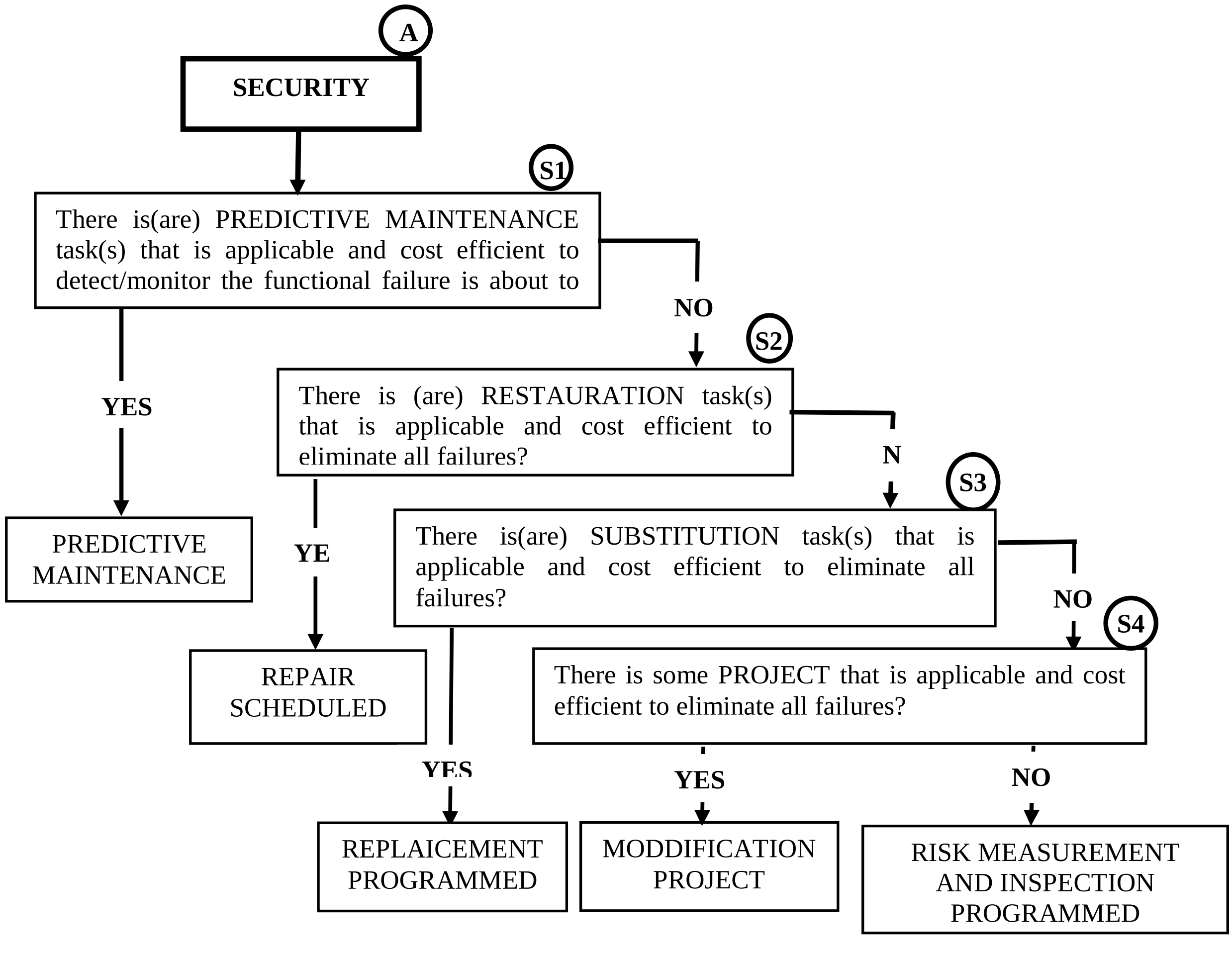


Figure 3. Logic Decision Diagram

Fox et al.(1994), mentioned that the TMI Classic used the same process of implementing the RCM using the same steps used in the original work of the commercial aircraft industry and the process of implementation follows four basic principles:

- Preserve the functions of the systems;
- Identify failure modes of specific equipment that may nullify these functions and cause a functional failure;
- Determine the priority to be attributed to each failure mode because not all functions and functional failures are the same; and
- For failure modes of high priority, define maintenance tasks preventive applicable and effective.

3.1 Selection of the System

As showed at the beginning of this work, USEXA executes great number of the activities.

The process flowchart showed in Fig. 2 is suitable to define the productive systems of the facility, however beyond of the productive systems, the USEXA is also composed of the support systems, e.g. effluents treatment unit, uranium recovery unit and utilities.

Utilities unit corresponds to all support systems of the facility like the boilers for production of the steam, compressed air system, ammonium tankage system, nitric acid system and chilled fluoride acid tankage.

The chilled fluoride acid tankage was chosen because of the relative complexity in the design and mainly because of the risks associated to operation and maintenance tasks of the unit.

The AFH tankage importance is because the acid is the raw material for production of the products of USEXA being the first input for hydrofluorination in the production of uranium tetrafluoride (UF_4). The second point is the use for production of fluorine in electrolytic cells. The gaseous fluorine is used in the last step of the conversion that converts UF_4 to uranium hexafluoride (UF_6).

3.2 Defining the boundaries of the AHF tankage

To apply RCM methodology it is necessary to define clearly the boundaries of the system that will be studied in order to restrict the analysis for the system and their main functions.

The boundaries of the AHF tankage are defined in the schematic draw of unit as shown in Fig. 4.

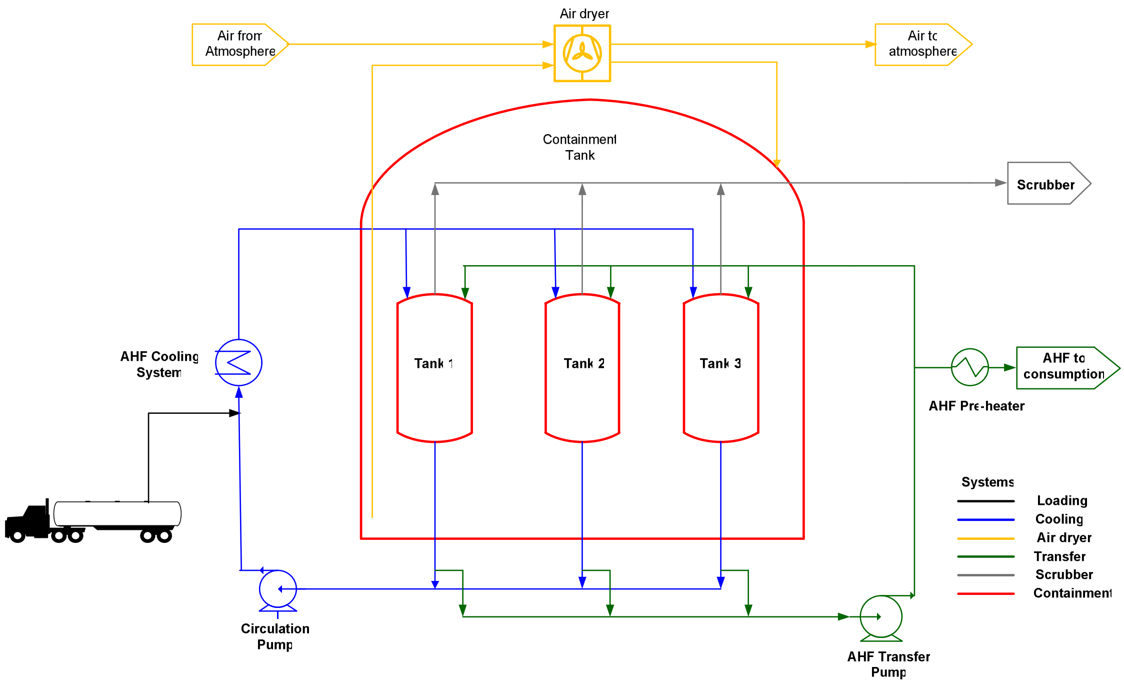


Figure 4. Schematic draw of AHF tankage

From Fig. 4 it is possible to define the boundaries of the unit of AHF tankage:

- Loading: the boundary is from the hoses that are connected to the valves that control the inlet of pressurized air used to transfer the AHF;
- Transfer: the boundary is the circuit between the transfer pump and preheater used to deliver the AHF to the plant;
- Pressure control: the boundary is the control valve system before the scrubber;
- Moisture control: the boundary is entrance and exit of air dryer; and
- Containment: the boundaries are all structural parts in direct contact with acid considering the pieces of equipment, pipes, valves and the storage and containment tanks.

3.3 System description

The analysis as for RCM implementation was based on plant design and there is still no database for maintenance reports in order to define the frequency of failures of the pieces equipment and what maintenance policy was used during the plant operation.

The system description was developed considering the simplified engineering flowcharts for each one of the subsystems, alarm lists, items and components of the AHF tankage systems.

The subsystems definition is based on main six functions that define the AHF tankage as follow:

- Loading;
- Cooling and acid storage;
- Acid transfer for consume;
- Air drying inside of the tanks;
- Pressure control of the tanks;
- Containment structural for acid

The following is the definition of items and components of the unit:

- Items: pipe, control equipment, monitoring and safety;
- Components: valves, transmitters, indicators, alarms, pumps, heat changers, position switch and level switch.

Figure 5 shows an example of the simplified engineering flowchart for loading step used to help the system analysis and implementation of RCM. It is stressed that the analysis was performed for all subsystems listed on engineering flowcharts.

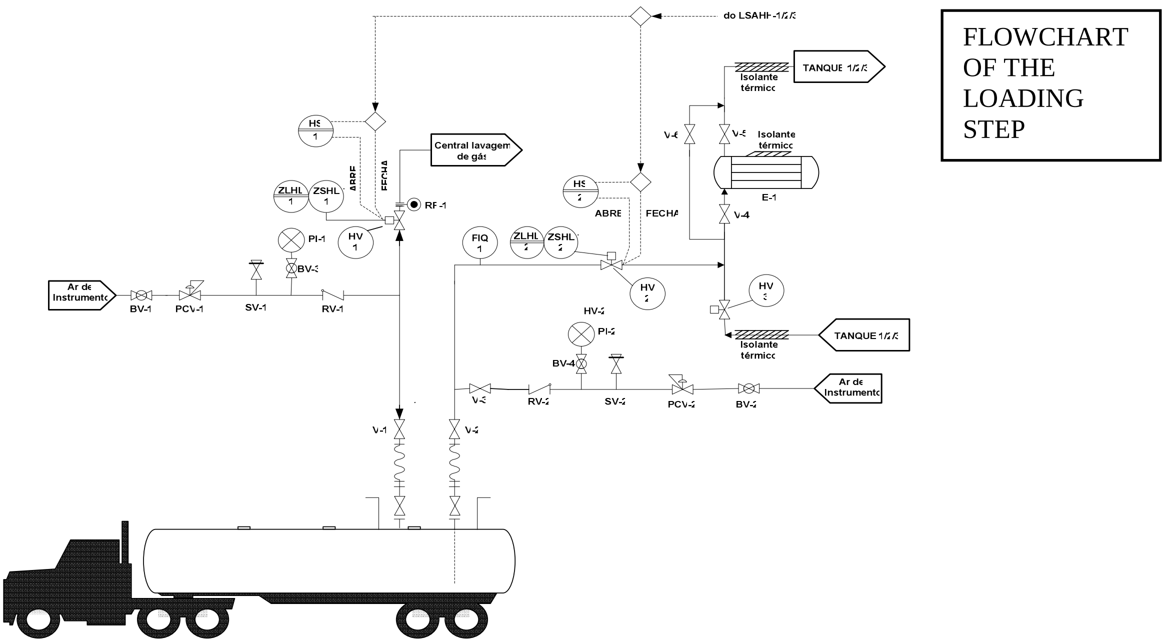


Figure 5. Example of the simplified flowchart of the loading step.

According to the flowchart shown in Fig. 5 you can check the diversity of items relating to the transfer step including the interlock valves "on-off" to ensure safety in operation.

3.4 Function and functional failures of AHF tanking

One of the stages of the implementation of RCM aims at identifying the functions and failures for components and subsystems. The practical form of presentation is a table form in which it is identified the item or component with its respective function and functional failure.

Table 3 shows the spreadsheet describing the functions and functional failures related to loading step.

3.5 FMEA Proposition

The RCM proposition is based on the elaboration of the FMEA of the loading subsystem considering the failure mode and effect for each item considering all steps since loading of the AHF tanks until supplying of the AHF to the plant. The FMEA was performed based on the flowcharts aiming at analyzing the severity (how the system is affected by the failure mode of the component), occurrence (how frequent is the occurrence of a given failure mode) and detection (how easy is to detect the development of the component failure mode) to determine the risk priority number (RPN) (MOUBRAY, 1994; SMITH & HINCHCLIFFE G., 2003)

Table 3 – Items roll from loading (functions and failures)

RCM	**SPREADSHEET DESCRIPTION OF FUNCTIONS AND FUNCTIONAL FAILURE**	
Unit	**AHF TANKAGE**	**LOADING**
ITEM	**FUNCTION**	**FUNCIONAL FAILURE**
Pipe	1-Conduct AHF from ISO tank to storage tanks. 2-Pressurize instrument air pipe. 3-Restrict passage of the pressurized air.	1-Appears leak; can not transfer the AHF to tanks. 2- Appears leak; can not transfer the AHF to tanks. 3-Not restrict the passage of the pressurized air.
Control	1-Control the pressure and flow for transferring the acid into the tanks. 2- Control the pressure and flow of the compressed air to ISO tank and the clean of transfer acid pipe. 3-Open and close the control valves.	1-Not control the pressure and flow for transferring the acid into the tanks. 2-Not control the pressure and flow of the compressed air to ISO tank and can not clean the pipe of the acid transfer. 3-Not open and close the control valves.
Monitoring	1-Show the line pressure. 2-Show the position of the control valve. 3-Show the flow and mass of acid transferred.	1-Not show line pressure. 2- Not show the position of the control valve. 3- Not show the flow and mass of acid transferred.
Security	1-Relieve the pressure of the instrument air pipe. 2-No permit counterflow of the acid by instrument air pipe. 3-Block the passage of acid or instrument air.	1- Not relieve the pressure of the instrument air pipe. 2- Permit counterflow of the acid by instrument air pipe. 3- Not block the passage of acid or instrument air.

The RPN is a result of product between indexes for severity, occurrence and detection. For each of those indexes a numerical scale between 1 and 10 was considered in the analysis. The higher the numerical value the higher is the severity, frequency of failure or difficult to detect failure mode development.(MOUBRAY, 1994)

An example of the use of the RPN score is shown on Pareto chart presented in Fig. 6 considering all items from tankage with RPN greater than 200.

The chart in Fig. 6 shows that the items connections and hoses are the ones with higher RPN score.

The second group, which includes the items with RPN score between 300 and 250, is represented by the AHF Heat Exchangers the AHF and blockage valves.

The third group of items that present RPN score below 250 in composed by the valves "ON-OFF ", containment tanks structure (T-4), level indicator transmitter, temperature indicator and storage tanks structure (T-1/2/3).

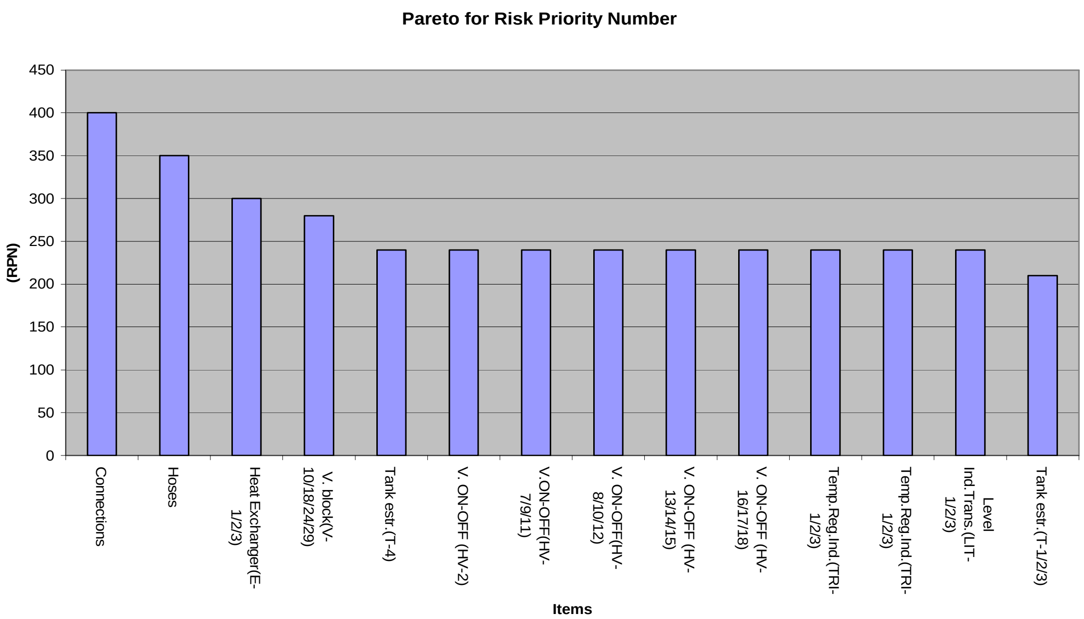


Figure 6. RPN graphic versus items of the AHF tankage

3.6 Decision Diagram

The last stage of implementation of Reliability Centered Maintenance is the use of the Decision Diagram which is based on the results of FMEA analysis aiming at the selection of the maintenance tasks for the critical components.

The selection of critical of the Refrigerated Anhydrous Hydrofluoric Acid Tanking Unit (C10.49) is based on the RPN assessment conducted in the previous section and the proposed maintenance tasks are:

- Hoses: perform leakage tests with compressed air in a bench with pressure equal to 1.2 times the normal operation pressure for a period of 30 minutes. Within this period there should have no pressure drop in the hose. The test must be performed before and after its use in the field.
- Connections: a) conduct periodic visual inspections in the flanges and connections of the line, b) re-tightening of sheaths to ensure the seal between the flange and gasket in PTFE to reduce leakage of AHF.
- Level Transmitter (LIT-1/2/3): the item has electronic board with random failure so the corrective maintenance with replacement after failure is recommended.
- Heat Exchanger (E-1/2/3) continuous monitoring of the temperature of ethylene glycol in the temperature indicator (TI-1).
- Indicator, recorder and alarm of the AHF: safety item with intervals of calibration defined by a qualified company with certificated assurance.
- AHF sensor (AIT-1): safety item with intervals of the calibration defined by a qualified company with certificated assurance.
- Conductivity sensor (CRI-1): the item has electronic board with random failure so the corrective maintenance with replacement after failure is recommended.
- Check Valves: perform preventive maintenance tasks with visual inspection and re-tightening of screws of the plug.
- Control valves: a) perform predictive maintenance through the analysis of the signature of the valve, b) periodical visual inspection for leaks and re-tightening of screws of the plug, c) verify the level of humidity of compressed air in order to prevent ice formation in pneumatic or solenoid valves.
- Control Valves (HV-7/9/11): safety item in which the valve can lock in the closed position. In this condition the maintenance of the valve must be corrective is in an unsafe condition with possible leakage of AHF. Solution: change the design of the output pipes from the (T-1/2/3) tanks installing another parallel pipes with check valves aiming at tank drainage before the maintenance operation of the valve, as shown in the Fig. 7.

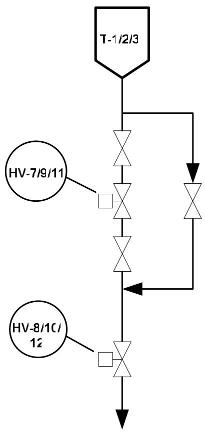


Figure 7. Change design of the output pipes from the tanks (T-1/2/3)

- Structure of the tank (T-4): Periodic visual inspection inside of the tank. Visual inspection in gasket of the hatch used to access the tank.
- Pumps (P-1/2): Predictive maintenance and visual inspection.
- Structure of the tank (T-1/2/3): safety item regulated by NR-13 standard which establishes that pressure vessels that operate below 0 ° C are rarely subject to severe deterioration. The standard also requires periodic internal inspection to measure the thickness of the sheet metal every two years and hydrostatic testing every 20 years. The standard NR-13 also establishes in Article 13.6.2 installation of pressure safety valve.
- High Conductivity Alarm (CAH-1): item can fail randomly and therefore corrective maintenance is recommended with replacement after failure.
- Safety valve (SV-1/2/3): safety item with visual inspection in bench in order to observe internal conditions.
- Pipe: visual analyzes and wall thickness measurement each two years.
- Manometers (PI-8/9): routine inspection and replacement in case of failure.

- Temperature Register Indicator (TRI-1/2/3): the item has electronic board with random failure and consequently a corrective maintenance practice is recommended.
- Register Level Indicator (LRI-1/2/3): the item has electronic board with random failure is consequently a corrective maintenance with the exchange after failure.
- Pre heater (E-4): on-condition monitoring by temperature indicator controller (TIC-1).
- Thermal Insulation: periodic visual inspection. The original design requires the thermal insulation should involve all valves, instruments, flanges and fittings of the line, but this situation could lead to hidden failure in the case of leakage of AHF. The proposition is that the items of the pipes should be inspected visually and should not be wrapped with insulating material. Leakages caused by corrosion on the flanges can be evidenced by visual inspection.

4. CONCLUSIONS

The proposition for implementation of the Reliability Centered Maintenance philosophy to Anhydrous Fluoride Acid Chilled Tanking System at unit of Production of Uranium Hexafluoride evidenced the risks associated with handling of that acid.

The proposition was based on elaboration of the FMEA datasheet executed for all items listed in the design drawings. In the future, when the C10.49 unit will be operating, the document can be updated and the RCM analysis improved for effective maintenance of the plant.

The study also evidenced the need to change the design of pipes coming out of storage tanks with the purpose of increasing the safety of the maintenance operation of the valves that are installed just below the tanks.

Other highlights of this work was to evidence the vacancy design in order to attend the NR-13 standard that establishes the installation of the safety pressure valve for tanks with fluid "A" class – toxic with threshold limit value (TLV) ≤ 20 ppm and also to vessel category III.

The thermal insulation must be removed in places where pipe flanges, valves and instruments are installed aiming at checking corrosion in the weld and thus avoiding hidden failures in these locations.

The study also demonstrated the efficiency of the FMEA analysis to mitigate design failures and to support design reviews. It can also support updates in the maintenance tasks when the plant is operational, taking in view failure reports.

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