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Technical and Economic Study of Trays Collapse in Crude Distillation Column C1 at RA1K – Skikda Refinery

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Abstract

This study focuses on a common problem in the distillation column C1 of the atmospheric distillation unit at the Skikda refinery RA1K which is the trays collapse. This work analyzes the various causes of trays collapse in the column C1, which range from operational, mechanical to human factors. The analysis is supported by the Bow-tie method that integrates top event, causes, consequences, preventative and protective barriers to avoid the problem and mitigate its impact. Our work examines also the resulting economic consequences of the collapse at the unit level and for the refinery as a whole including maintenance and repair costs and the decline in production of the most valuable and in-demand petroleum products. The aim is to provide a comprehensive overview combining technical and economic analysis to understand the phenomenon of trays collapse and reduce its frequency.

Keywords: Crude distillation column; Trays Collapse; Bow-tie analysis; Economic assessment; Skikda Refinery.

Résumé

Cette étude porte sur un problème fréquent dans la colonne de distillation C1 de l'unité de distillation atmosphérique de la raffinerie Skikda RA1K qui est la chute des plateaux. Elle analyse les différentes causes de cet effondrement, qu'il s'agisse de facteurs opérationnels, mécaniques et humains. L'analyse s'appuie sur la méthode du nœud papillon, qui permet de relier l'événement principal, les causes, les conséquences, ainsi que les barrières préventives et de protection mises en œuvre pour éviter le problème et en atténuer ses effets. L'étude aborde également les répercussions économiques de la chute, tant au niveau de l'unité que pour la raffinerie dans son ensemble, notamment les coûts de maintenance et de réparation et la baisse de production des produits pétroliers les plus précieux et les plus demandés. L'objectif est de fournir une vue d'ensemble complète, combinant analyses technico-économiques, afin de comprendre le phénomène d'effondrement des plateaux et d'en réduire la fréquence.

Mots clés : Colonne de distillation atmosphérique ; Pétrole brut ; Effondrement des plateaux ; Méthode Bow-Tie ; Évaluation économique ; Raffinerie de Skikda.

ملخص

تركز هذه الدراسة على إحدى المشاكل الشائعة على مستوى عمود التقطير C1 بوحدة التقطير الجوي في مركب مصفاة سكيكدة والمتمثل في سقوط الصواني على مستوى هذا العمود. يحلل هذا العمل الأسباب المختلفة لانهيار الصواني في العمود C1 والتي تتراوح بين عوامل ميكانيكية، تشغيلية وبشرية. كما تم تدعيم التحليل بمنهجية عقدة الفراشة التي تجمع بين الحدث المركزي، الأسباب، النتائج، الحواجز الوقائية والحمائية لتجنب المشكلة وتخفيف اثارها. كما تتناول الدراسة التداعيات الاقتصادية المترتبة على السقوط على مستوى الوحدة والمصفاة ككل بما في ذلك تكاليف الصيانة والإصلاح وانخفاض انتاج المنتجات البترولية الأكثر قيمة وطلبا. الهدف من هذا العمل تقديم رؤية شاملة تجمع بين التحليل التقني والاقتصادي لفهم ظاهرة سقوط الصواني والحد من تكرارها.

الكلمات المفتاحية: عمود التقطير الجوي؛ النفط الخام؛ انهيار الصواني؛ منهجية بو-تاي(Bow-Tie) ؛ التقييم الاقتصادي؛ مصفاة سكيكدة.

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إهـــــــــــــداء

إلى تلك الطفلة الصغيرة التي كانت تردد دائمًا:

" يوما ما سأتخرج كمهندسة بتروكيمياء"

- هنيئًا لكِ صغيرتي.. ها قد تحقق الحلم!

إلى من أهدت تلك الطفلة خوذة بيضاء وقالت:

"طاردي أحلامك".

- إلى أمي.

List of figures

<u>**Chapter I**</u>

<u>**Chapter II**</u>

<u>**Chapter III**</u>

List of tables

Table of Contents

Chapter III: Technical study of trays collapse

List of abbreviations

BSW	Basic Sediment and Water
CCR	Conradson carbon residue
CDU	Crude distillation unit
CEPCI	chemical engineering plant cost index
HGO	heavy gas oil
HVGO	heavy vacuum gas oil
Kero	kerosene
LGO	light gas oil
LPG	liquefied petroleum gas
LS	low pressure steam
LVGO	light vacuum gas oil
MH	manhole
MS	medium pressure steam
MVGO	medium vacuum gas oil
RCO	Reduced crude oil
TBP	True boiling point

General Introduction

General introduction

Petroleum is one of the most important energy sources, playing a vital role in industrial and economic development. With industrial progress and the continuous increase in demand for petroleum products, the refining sector has received considerable attention, as it transforms crude oil into products that meet market needs.

Distillation is the first and the most important step in the refining process where crude oil is separated into several products such as LPG, naphtha, kerosene, light and heavy gas oil and the atmospheric residue. This process takes place inside the distillation column, which is considered one of the most important industrial equipment in any refinery and distillation unit.

These columns consist of several components, the most important of which are the trays, due to their crucial role in ensuring efficient separation by guaranteeing contact between the vapor and the liquid.

The Skikda refinery is the largest refining complex in Algeria, comprising several units, including two atmospheric distillation units that separate crude oil into different fractions. These fractions are then transferred to various processing and conversion units. Given the importance of this process, any disruption or malfunction in the unit affects its stability and efficiency.

Among the most significant problems facing distillation columns is the phenomenon of trays collapse, a serious issue that impacts separation efficiency and the stable operation of the unit therefore, this work focuses on understanding this phenomenon from all angles in order to prevent its recurrence and minimize its occurrence in the future.

We have structured our work into four chapters:

- In Chapter 1, we provided an overview of the Skikda refinery and the assignment unit.
- In Chapter 2, we presented the distillation process and the distillation column from all their perspectives.

- In Chapter 3, we conducted a technical study of the collapse problem in column C1, outlining the possible causes of collapse and how they contribute to it. This chapter was further supported by the Bow-tie analysis methodology.
- In Chapter 4, we conducted an economic study examining the direct and indirect economic repercussions of this phenomenon.

This topic was chosen due to its significant importance at the unit level and in response to the increasing concern of the production and inspection team.

Chapter I:

Overview of the Skikda refinery and the assignment unit

I.1. Introduction

This chapter aims to provide a comprehensive overview of the Skikda refinery, reviewing its mission and position within the refining sector and describing its various production units while highlighting the role of each in the crude oil refining chain. Particular emphasis is placed on the atmospheric distillation unit, as it is the subject of our study.

I.2. Mission of the refinery

The Skikda refinery complex, named RA1/K, has the mission of transforming crude oil from Hassi Messaoud with a processing capacity of (18 million t/year), as well as imported reduced crude (277,000 t/year) [1].

I.3. Geographical Location

This refinery is situated in the industrial zone 7 km east of Skikda and about 2 km from the sea. It covers an area of 190 hectares and currently employs approximately 1,280 workers. It is supplied with Algerian crude oil from Hassi Messaoud.

Crude oil is transported via a pipeline over a distance of 760 km from the oil fields to the complex [1].

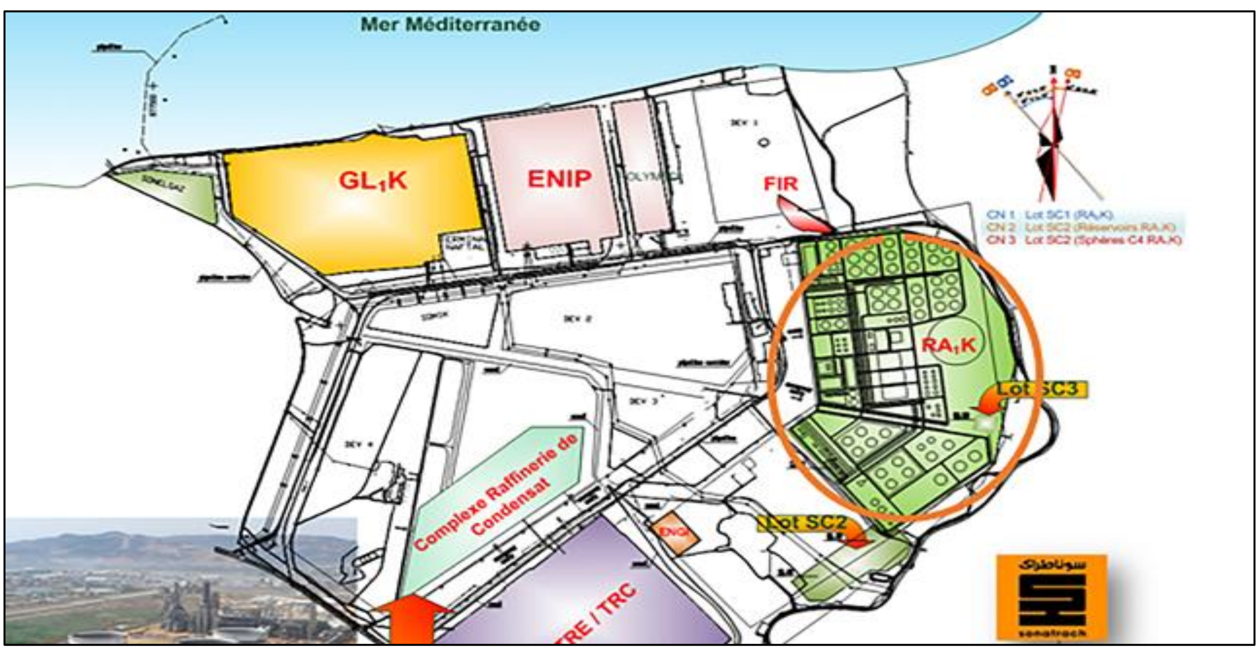

Figure I.1: Geographical location of RA1K [2].

I.4. Construction history

The building of this refinery dates back to January 1976, under a contract signed between the Algerian government and two Italian companies SNAM PROGETTI et SAIPEM on April 30, 1974.

The construction works began on January 2, 1976 and the production units gradually became operational until March 1980 [1].

I.5. Presentation of the different production units

The refinery comprises the following units [1]:

- Units 10 - 11: Atmospheric distillation (Topping).
- Units 30 - 31 - 104: Treatment and gas separation (GPL).
- Unit 70: Vacuum distillation (Bitumen production).
- Unit 100: Pretreatment and catalytic reforming (Magnaforming).
- Units 101 - 103: Pretreatment and catalytic reforming (Platforming).
- Unit 200: Aromatics extraction.
- Unit 400: Crystallization and paraxylene separation.
- Unit 500: M-xylene isomerization.
- Units 700 - 701 - 702 - 703: Light naphtha isomerization.

In addition to the utilities:

- Unit 62: Water demineralization.
- Unit 600: Storage, mixing and shipping (Melexe).
- Unit 1050: Thermo-electric power plant.
- Unit 900: Hydrogen purification.

I.5.1. Units 10 - 11 0

Topping or atmospheric distillation, aims to fractionate crude oil into different stabilized fractions that can be used to obtain finished products

These two units process crude oil from Hassi Messaoud to obtain the following products: LPG, Isopentane, Naphtha A, Naphtha B, Naphtha C, Kerosene, Light Gas Oil, Heavy Gas Oil and Residue.

I.5.2. Units 100 - 103

Magnaforming and Platforming units aim to transform the medium and heavy naphtha obtained from Topping into reformate used as a filler for aromatic units (units 200 and 400). This transformation results in an increase in the octane rating from 45 to 99, thus allowing the reformate obtained to be used in the manufacture of gasoline.

I.5.3. Unit 200

The aromatics extraction plant was designed to extract aromatics from reformed gasoline, which will subsequently be fractionated into highly pure benzene and toluene.

The feed consists of the light reformate cut, either directly or via a reservoir from the C_5 reformate splitter column of Unit 100.

I.5.4. Units 30 - 31 - 104

These units are designed to process liquefied gases from units 10, 11, 100, and 103 in the following order:

- Unit 30: processes the liquefied gas from unit 100, particularly the gases from the top of column C7 where the LPG is separated from the pentane.
- Unit 31: receives the gases from the top of the gasoline stabilization columns of the two Topping units.
- Unit 104: was recently designed in conjunction with the new Platforming unit 103 to process the LPG from that unit

I.5.5. Unit 400

This unit is designed to recover para-xylene, a product in high demand on the market.

The feed from the Magnaforming unit allows, through crystallization, the separation of para-xylene from other xylenes: metha, orth and ethylbenzene.

The para-xylene is sold as is, while the rest can be used as a base for producing gasoline or sold as a xylene mixture that can be used as a solvent in the manufacture of paints, etc.

I.5.6. Unit 500

The aromatics isomerization unit was designed to recover the filtrate from the crystallizers of Unit 400 and isomerize it.

The resulting isomerate will be separated into two main fractions:

- A fraction rich in benzene, sent to Unit 200.

- A fraction rich in paraxylene, sent to Unit 400.

The main purpose of this unit is to increase p-xylene production.

I.5.7. Unit 700 - 701 - 702 - 703

Their goal is the conversion of normal paraffins into isoparaffins, a reaction increasingly sought after by refiners to obtain a high octane rating without the addition of additives.

Paraffins ranging from butane to hexane can be isomerized using modern, highly active platinum-based catalysts.

Isomerization can be taken to the extreme by using distillation and/or molecular sieving to separate unconverted normal paraffins. C5-C6 cuts can also be fully isomerized into high-octane components, highly sought after for the gasoline pool.

The isomerization process has become a valuable tool for refiners to expand their product range and improve their quality, while increasing operational flexibility and profitability. Furthermore, the production of these high-octane, aromatic-free constituents reduces the contribution of aromatic-rich reformate to the gasoline pool, thus improving gasoline quality in terms of environmental protection, which is a very important factor today.

At the Skikda refinery, two trains have been installed for the isomerization of the light fraction of topping gasoline (U10 & U11) to provide an aromatic-free additive to the gasoline pool for fuel production.

I.5.8. Unit 70

Unit 70 was designed to process 271,100 tons per year of imported reduced crude oil (BRI), which can be:

- Feed A: Medium TIA Juan residue (372°C+).
- Feed B: Heavy TIA Juan residue (450°C+).
- Feed C: Kuwaiti crude residue.

The unit consists primarily of a vacuum distillation column and a bitumen oxidation reactor. The bottom product is ordinary road bitumen, which is sent:

- Part to storage.
- The other part as feed to the oxidation section where it will be oxidized to oxidized bitumen using air.

I.5.9. Unit 600

Mixing, loading, and shipping, its responsibilities include:

- Storing the various loads and products from the units in bins.
- Shipping products to different storage depots, for example, the El Kheroub depot.
- Blending diesel fuels.
- Monitoring the loading of products at the port of Skikda.

I.5.10. Unit 1050

This is the refinery's nervous system, comprised of 11 sections:

- Section 62: for the production of demineralized water.
- Section 1020: for water cooling towers.
- Section 1030: for the storage and pumping of reservoir water or drinking water.

- Section 1040: for the storage and pumping of fire-fighting water.
- Section 1050: for the generation of steam for the boilers.
- Section 1060: for the recovery and treatment of condensate.
- Section 1070: or Fuel-gas system.
- Section 1080: for the production of instrument air and service air.
- Section 1100: for effluent treatment.
- Section 1110: for nitrogen (N2) production.
- The electricity production section.

I.5.11. Unit 900

Its aim is to increase the purity of the hydrogen produced by unit 100, in order to send it to other hydrogen-consuming units (unit 500…) [1].

I.6. Presentation of the assignment unit

The atmospheric distillation unit of the Skikda refinery or Topping is being revamped to process 27,000 metric tons per stream day, the equivalent of 9,000,000 t/year of Hassi Messaoud crude oil. It produces the following petroleum fractions [3]:

- Combustible gas.
- Liquefied petroleum gas (LPG).
- The C6 cut.
- Naphtha A.
- Naphtha B.
- Naphtha C.
- Kerosene.
- Light Gas Oil (LGO).
- Heavy Gas Oil (HGO).
- The atmospheric residue.

The design capacity after the renovation of the atmospheric distillation unit is 8,250,000 t/year for 8,000 h/year of operation, according to the warranty. However, the current design capacity is 9,000,000 t/year [3].

I.6.1. Process description

The atmospheric distillation unit is designed to fractionate crude oil into different petroleum fractions which can be either finished and sent directly to storage or used as feed for other units.

It is composed of the following parts [3]:

- Crude oil desalting
- Feed preheating
- Crude oil fractionation column
- Side draw stripping columns
- Naphtha fraction stabilization columns
- C6 cut separation column
- Separation columns for naphtha fraction A, B, and C.

The process of the CDU is schematized in the two figures below:

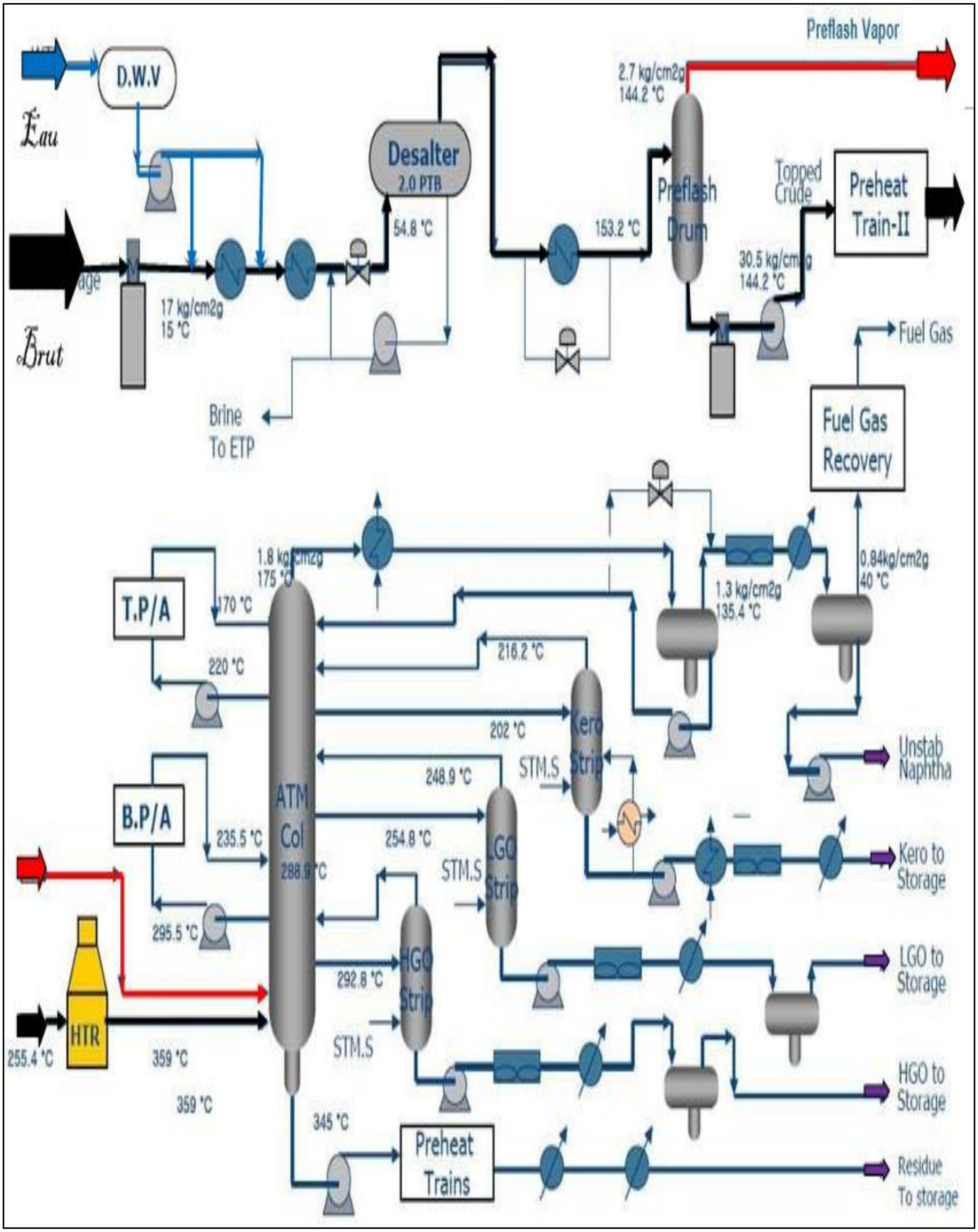

Figure I.2: Process Schema of the Atmospheric Distillation Unit -1st part [3].

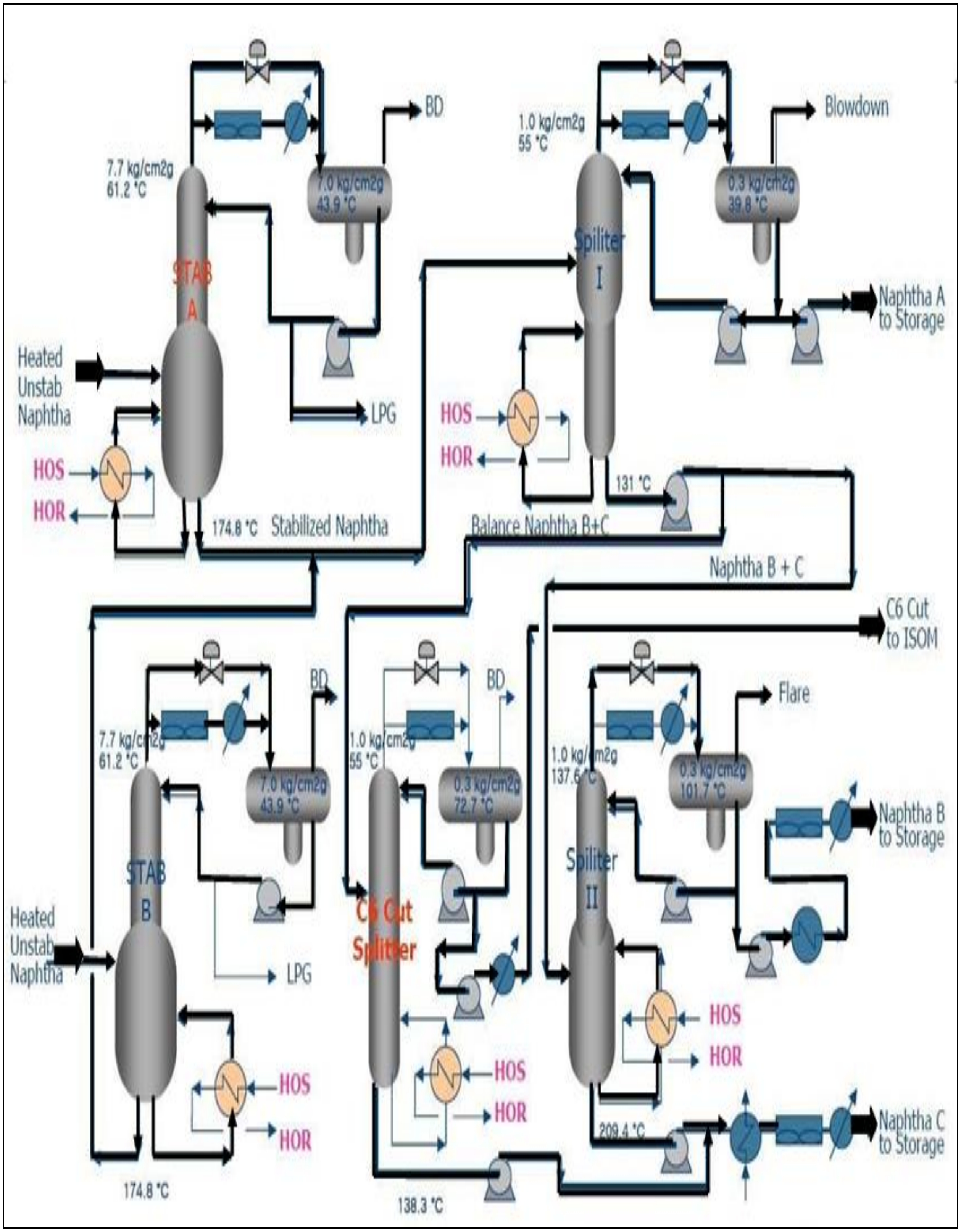

Figure I.3: Process Schema of the Atmospheric Distillation Unit -2nd part [3].

I.6.2. Charge and product specifications

Understanding the physicochemical properties of the crude oil that feeds the unit is an important step to understand its behavior during the distillation process, the table I.1 illustrates these properties.

Table I.1: Charge specifications [3].

specifications	**Values**
Specific gravity (°API)	44,7
Density at 15°C	0,8025
Characterization factor K	12
Kinematic viscosity at 37.8°C (cSt)	1,989
Dropping point (Per point) (°C)	-52
Flash point (°C)	< 20
Total sulfur content (%wt)	0,13
Hydrogen sulfide content (ppm)	0
Ash content (%wt)	< 0,005
Salt content (e.g., NaCl) (%wt)	< 0,001
Wax content (%wt)	2.4
Asphalt content (%wt)	0,06
CCR content (%wt)	0,83
BSW (%vol)	Traces

The specifications of the products obtained at the atmospheric distillation unit are mainly defined according to the TBP distillation ranges.

the products and their corresponding TBP distillation intervals are presented in the table below:

Table I.2: Product specifications [3].

Product	**Distillation TBP** initial Point and final Point (°C)

LPG	-
Naphtha A	C5 - 65
Naphtha B	65 - 150
Naphtha C	150 - 180
C6 Cut	-
Kerosene	181-235
Light gas oil	235-320
Heavy gas oil	320-360
Atmospheric Residue	>360

I.6.3. Mass balance of the atmospheric distillation unit

The table below represents the input and output flows of the unit expressed in mass balance (kg/h).

As we can see from the table, the difference between the total charge flow rate and the total product flow rate is 1 kg/h and this confirms the validity and consistency of the mass balance that was performed.

Table I.3: Mass balance of the unit [3].

Designation	**Mass flow rate (kg/h)**
Crude oil from storage	1.130.618
Desalter water	70.004
Stripping vapor of atmospheric residue	8.498
Stripping vapor of light gas oil	4.396
Stripping vapor of heavy gas oil	1.527
Total charge(feed) flow rate	**1.215.043**
Water containing salts desalter	72.892
Combustible gas	173
LPG to the gas treatment and separation unit (U30)	43.091

Naphtha A to storage	43.942
Naphtha B to storage	157.130
Naphtha C to storage	128.347
C6 cut to the isomerization unit	9.855
Treated kerosene to storage	93.751
Light gas oil to storage + excess kerosene	259.599
Heavy gas oil to storage	90.629
Atmospheric residue to storage	299.001
Acid water and oily water	16.632
Total product flow rate	**1.215.042**

I.7. Conclusion

This chapter covered all the structures of the Skikda refinery by reviewing its various structures and production units, with a particular focus on the atmospheric distillation unit, the unit under study. This provides a comprehensive overview of the industrial environment in which the study was conducted and an understanding of the unit's role within the crude oil refining chain.

The following chapter will address the theoretical aspects of the atmospheric distillation process and the distillation column, presenting its fundamental operating principles and components. This will lay the groundwork for understanding and analyzing the problem addressed in this study.

Chapter II:

Distillation

II.1. Introduction

Distillation from the Latin verb “destillare” i.e., to descend or to trickle. It is the most widespread separation process in several industries (chemical, pharmaceutical, and petroleum industries...)

This process is used in order to purify and to separate liquids by partial evaporation of the liquid and a successive condensation of the vapor obtained to return into a liquid, which leads to the separation of components based on their different boiling points [4,5].

II.2. The history of distillation

Distillation is one of the oldest processes, dating back thousands of years BC. In 1800 BC in Mesopotamia, it was used by King Zimri-Lim to manufacture medicinal and cosmetic products (perfumes, ointments, incense, essential oils, etc.).

In the first century AD, it was mentioned by the physician Pedanius Dioscurides after he observed condensation forming on the lid while heating mercury, which contributed to understanding its principles.

Between the second and third centuries, the process developed further after the invention of the distillation apparatus by Maria the Jewess or the Egyptian chemist Zosimos of Panoplies and his sister, who invented several distillation and condensation devices, such as reduction condensers, which facilitated the process. While other sources link the emergence of distillation to Arab chemists between the 8th and 9th centuries,

In the 11th century, Ibn Sina brought about significant development and change through his invention of a highly efficient distillation apparatus.

In the 14th and 15th centuries, the Turks spread distillation to many countries through their conquests of Europe [6].

II.3. The principle of distillation

The principle of distillation relies on the difference in boiling points related to molecular reactions, known as van der Waals forces.

When the molecule is bigger and heavier, i.e., has a greater weight, we have more dispersion forces (London) and this leads to the increase and the difference of the compounds' boiling points, thus allowing for their separation.

Dispersion forces (London) are one of the van der Waals forces, in addition to permanent dipole-dipole forces, and hydrogen-bonding forces [7].

II.4. Types of distillation used in petroleum industry

II.4.1. The atmospheric distillation

The setup of the atmospheric distillation unit is related to the processing of both light and heavy oil; therefore, many units are designed to deal with the two different types in order to produce raw materials that must be processed in subsequent units to produce various products of different specifications.

The capacity of the unit ranges from 10,000 to 400 thousand barrels per day, with different capacities, the unit must remain able to work efficiently about 60% of the design feed rate.

The units of good sizes are capable of processing 200,000 barrels per day, so from the economic side, the larger units are the preferable.

The atmospheric distillation units are the largest units in the refinery in terms of size and cost because they deal with very high flow rates.

The main products obtained from the unit include [8]:

- Light straight run naphtha.
- Gases.
- Heavy gasoline.
- Kerosene (also called light distillate or jet fuel).
- Middle distillates called light gas oil (LGO).
- Heavy distillates called heavy gas oil (HGO).
- Crude column bottoms called atmospheric residue.

The tray distribution for each product in typical designs is shown in Table below:

Table II.1: Tray distribution in a crude distillation unit [8].

Tray's number	Zone
10	Overhead product to kerosene
8	Kerosene to light gas oil
6	Light gas oil to heavy gas oil
6	Heavy gas oil to flash zone
6	Flash zone to atmospheric residue
3-4	Pumparounds

II.4.1.1. Process description

The first step is to pump the crude oil from the storage tanks, where impurities and water naturally settle to the bottom. Then, the crude is sent to a heat exchanger series where the heat of the column distillation products is used to gradually heat it before it enters the unit, typically raising its temperature to around 120-150°C (248-302 °F).The next step is desalting, which consists using a mixing valve to mix the crude oil with dilution water (5 - 6 vol %). This process removes the impurities from the crude oil, which are the salts dissolved in water droplets. It takes place in an electrostatic desalter where the salty water droplets collect under the influence of an electric field and then separate due to gravity (transitioning to the aqueous phase) [8].

Optimal energy use is a key factor in achieving the unit's economic feasibility. Therefore, after salt removal, the oil is preheated in products heat exchangers, which simultaneously allows them to be cooled to the appropriate temperature for pumping into storage tanks. According on the crude oil composition, its temperature is raised using a furnace, as preheating alone is insufficient. Therefore, partial evaporation of the crude oil is employed to ensure that most of the components entering the distillation column are in a vapor state, with the exception of the heavy fraction known as atmospheric residue. The transfer of the to a distillation column consisting of approximately 30 to 50 trays and measuring exactly 50 meters in height, to the flash zone located at the stripping section. As a result of the high rate of upward vapor flow, the column is designed with a larger diameter in this area to ensure that the vapors pass through smoothly without affecting the separation efficiency.

In order to strip the atmospheric residue of lights hydrocarbons and to lower the partial pressure of the hydrocarbon vapors in the flash zone, a steam is injected. After the hydrocarbons' evaporation and rising towards the top of the column, they condense and withdraw in the form of side streams, and this is due to this process which lowers the boiling point of the hydrocarbons.
The more the boiling points are reduced, the amount of vaporized hydrocarbons increases. The hot vapors come into contact with the colder vapor reflux down the column as they rise through the trays from the evaporation zone to the top of the column. The vapors condense in the overhead condenser, and some of the naphtha is returned to the column as a reflux.

The enthalpy of the feed provided the heat inside the column. however, to ensure efficient operation of the process, part of this heat is removed by both overhead condenser and liquid which is taken off at a point below a side stream tray that is cooled via the cold crude feed, then reintroduced to the column a few trays higher than the point of withdrawal, known as pump around stream. For the purpose of the improvement of the column's thermal efficiency and to decrease the furnace energy requirement the heat must be removed from the column at higher temperatures and from the condenser at lower temperatures[8].

In the presence of pump around streams, the required column size is smaller than in the absence of pump around streams, because these streams reduce the vapor flow rate throughout all the column. After cooling, a more fractionated liquid is mixed with a less fractionated liquid in trays above it; therefore, excessive use of these streams negatively impacts the fractionation process by reducing its efficiency

To control the initial boiling point of side draw products, these products are separated by steam at the bottom of the stripper, which contains trays. Separation can also be achieved by using a reboiler type side stream strippers. The final boiling point of the side stream is controlled by the flow rate of side stream products.

The overhead vapor is condensed at the top of the tower by heat exchange with the cool crude coming into the unit and by air and cooling water. The liquid product is known as light straight run naphtha, part of which is returned to the column as reflux to improve separation. Additional products such as heavy naphtha, kerosene, light gas oil (LGO), and heavy gas oil (HGO) are withdrawn at different levels above the feed tray, while the atmospheric residue is removed from the bottom of the column [8].

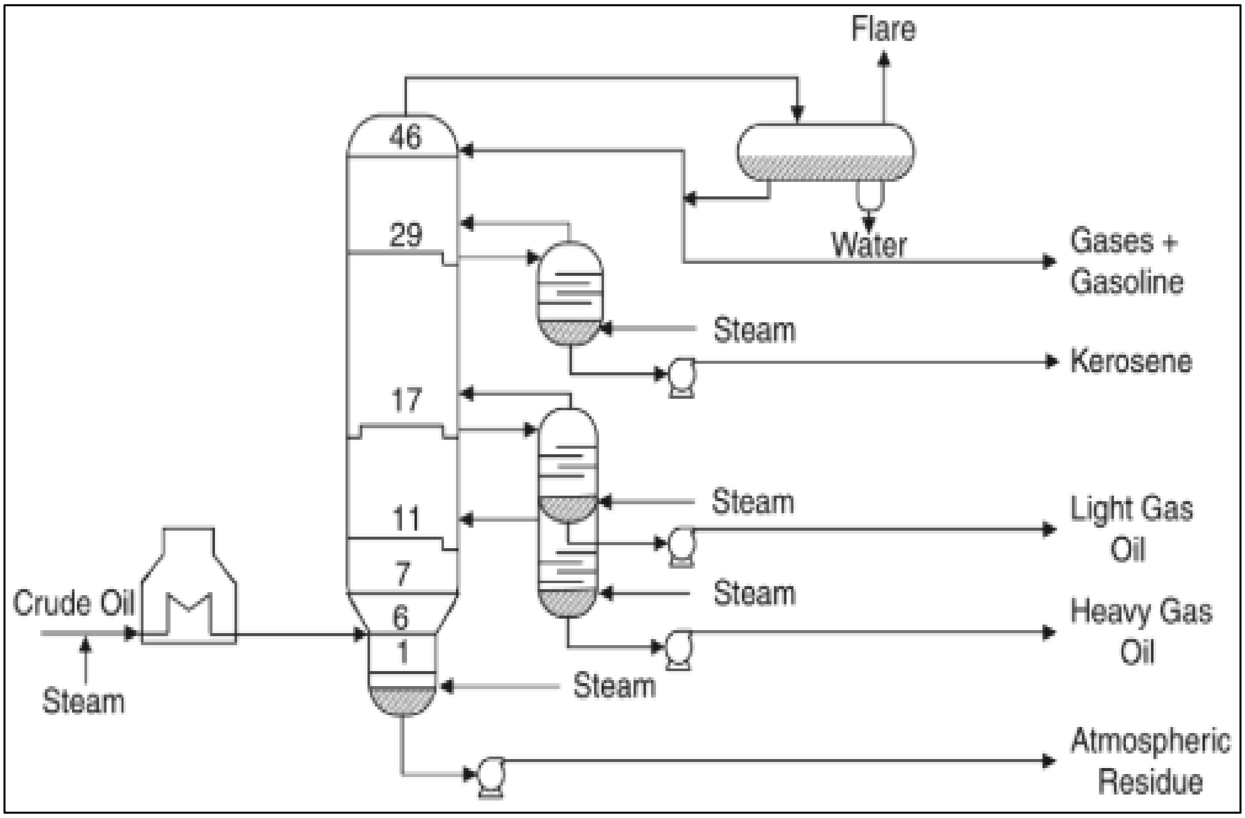

Figure II.1: Process flow diagram of an atmospheric distillation unit [8].

II.4.2. Vacuum distillation

This type of distillation comes after the atmospheric distillation, when the bottom of the atmospheric unit is fed to the vacuum distillation unit, with the aim of completing the distillation process and extracting more distillates from the atmospheric residue.

It is possible that the distillates contain impurities such as sulphur, metal and asphaltene, that is why the hydrotreating is used to get rid of these unwanted components.

The main distillates obtained from the unit include:

- Light vacuum gas oil (LVGO).
- Medium vacuum gas oil (MVGO).
- Heavy vacuum gas oil (HVGO).

- Vacuum residue.

Lubrication oil grade feed stocks can be produced in this unit. Selected types only can yield lube grade feed stocks; thus, its production varies according to the quality of the crude oil supplied to the refinery [8].

II.4.2.1. Process description

This unit is based on the atmospheric residues. In some cases, the residue is transferred

to storage first, and to control its viscosity for appropriate flow, its temperature is kept above 150°C. While in the other cases, in other cases, the vacuum unit receives the residue directly after it has passed through a crude preheat exchangers train in order to extract heat. The vacuum unit's own hot products are used to heat the residue in numerous exchangers.

Then, the temperature is raised to approximately 380-415 °C (716-779 °F) by means of a fired heater, and this is the final heating of the residue.

Steam is fed into the heater tube passes to reduce coke formation and thermal cracking which are which are operationally undesirable .

The vacuum tower receives the feed at the bottom of the column. A 3-5 vol% overflash is maintained, much like in atmospheric distillation, meaning that more vapors are created than all products removed above the flash zone.

This aims to manage the end point of the HVGO draw off tray by providing some fractionation between it and the flash zone[8].

The LVGO and two more fractions which are MVGO and HVGO are withdrawn like a distillate.

In order to remove the heat from the tower at a more favorable level from the HVGO pump around, the two fractions MVGO and HVGO are required.

Heat exchange zones and fractionation packing are used to equip distillation columns to lessen the pressure drop within the column, as a result, a low vacuum is produced at the bottom of the column, which contains valve trays.

The heavy ends condense with HVGO reflux in a wash and fractionation zone, through which vapors flow from the flash zone.

In the higher up, a sprays of liquid from the pump around or the internal reflux are used to divide the column into sections.

Ejectors or a combination of ejectors and liquid ring pumps are used to generate vacuum in the vacuum distillation units.

Gas is recompressed by ejectors through a nozzle where a stream of medium or low-pressure steam draws vapors from the column to the venturi part of the nozzle.

At the ejector outlet, the vapor phase is partially condensed using cooling water inside a heat exchanger. The overhead drum receives the liquid phase, while the vapor phase is transferred from the condenser to another ejector-condenser stage.

In dry or wet type vacuum distillation, a single pump can assume the role of two or three stages of ejectors that is why liquid ring pumps and rotor gas compressors are equivalents.

These systems do not require steam and can greatly decrease hydrocarbon-rich aqueous condensates in a system using ejectors. Ejector-equipped systems are far more adaptable and quicker to operate. lowered steam consumption and reduced installation costs compensate for the elevated investments needed by liquid ring pumps [8].

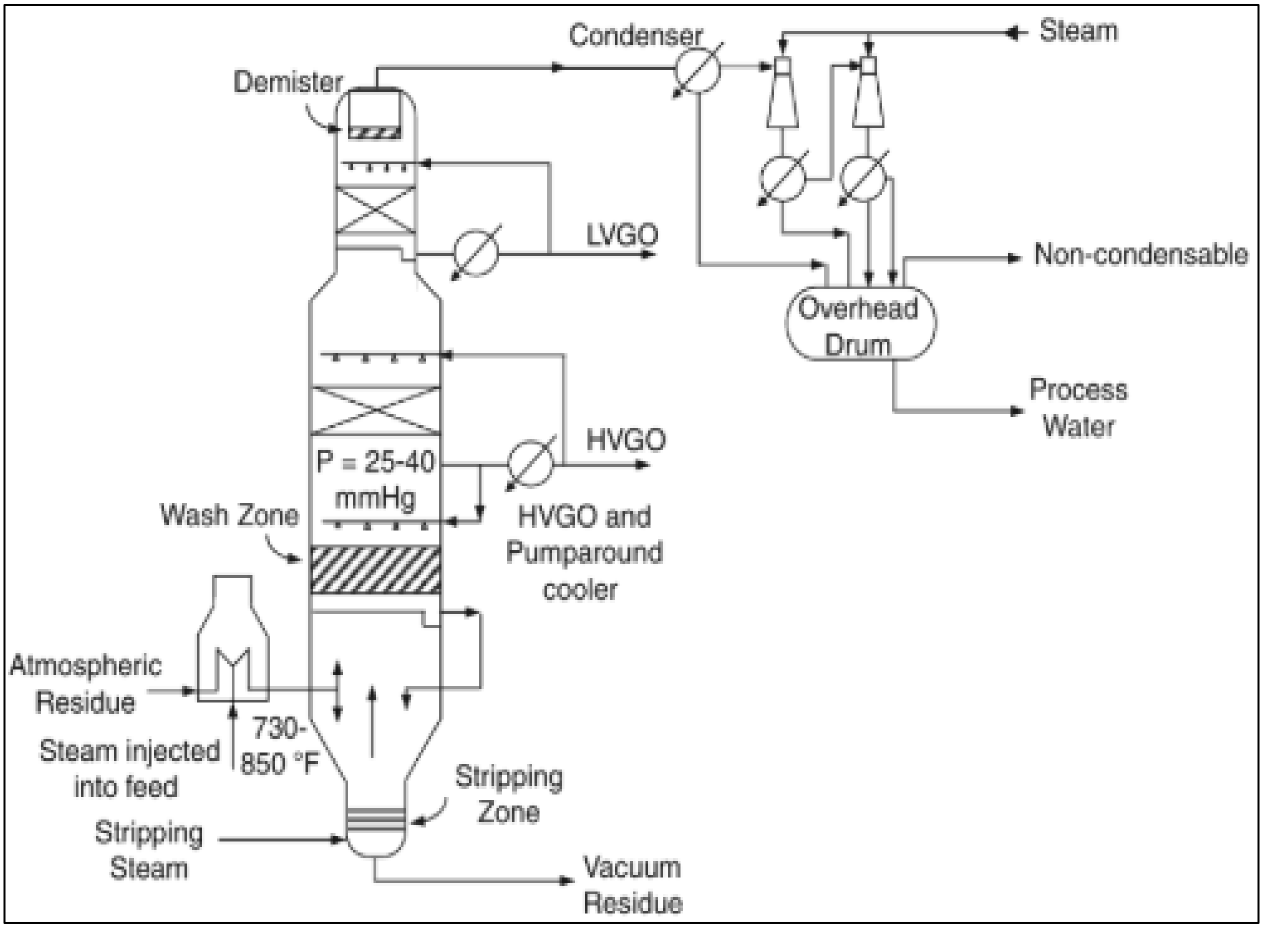

Figure II.2: Process flow diagram of vacuum distillation unit [8].

II.5. Definition and principle of a distillation column

Distillation column is a physical separation device which ensures the separation of a mixture of components based on mass and energy exchanges between the vapor and the liquid phases [9].

The operating principle of a distillation column at constant pressure. Phase equilibria using a temperature gradient created by a cold source. It contains devices ensuring intimate contact between the liquid and gas flows passing through it in counter-current flow; these devices are trays or packings. Evaporation enriches the more volatile elements from bottom to top, while liquids enrich the less volatile elements from top to bottom [10].

II.6. The description of a distillation column

A distillation column is a vertical cylindrical tower which is used to separate the components of the charge by making the liquid and vapor phases in contact [11].

It consists of many elements, as shown in the figure:

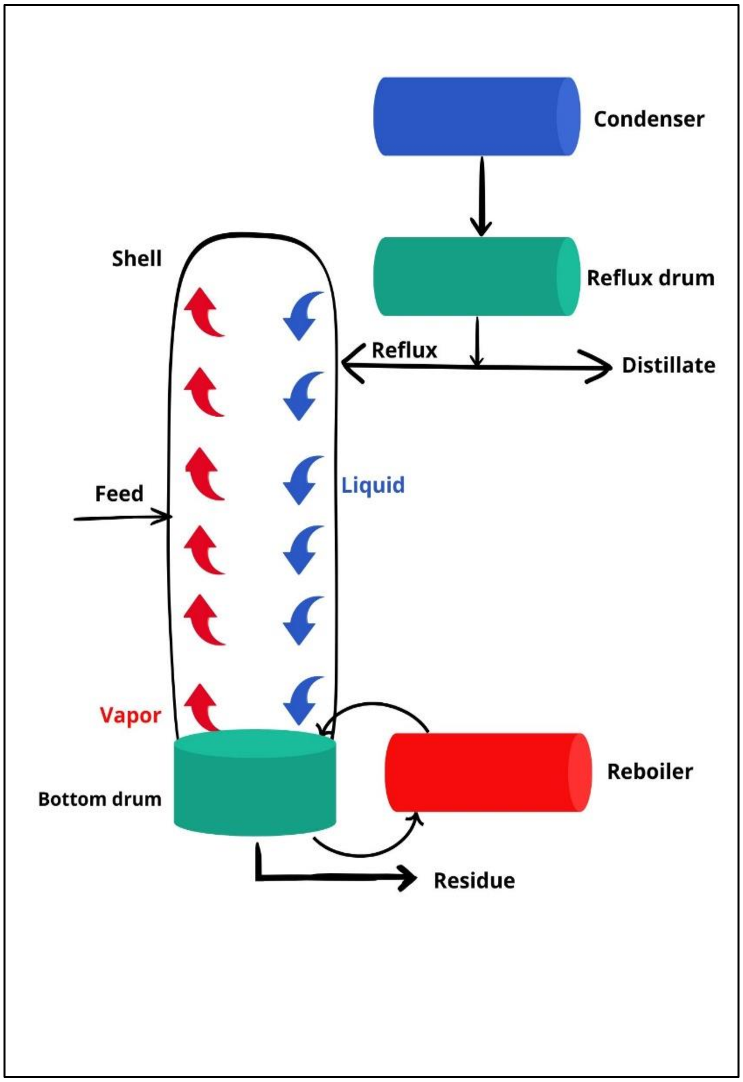

Figure II.3: Distillation column and its elements.

II.6.1. Shell

The column shell is the outer structure of the column which is designed to be resistant to pressure, dilation, and even natural phenomena such as wind and earthquakes.

The large variation in vapor flow rate and its physical properties between the bottom and top of the column can requires the column to adapt to operating conditions and to use a column with two or three diameters and this represents the most economical option. It may consist from sections of varying diameters.

Two main types of column shell can be distinguished: single piece shell and segmented shell [12].

II.6.2. Drums

There are two types of drums, the reflux drum at the top of the column which increases the internal flow rate of the liquid by increasing the reflux flow rate.

The bottom drum, which increases the internal flow rate of the vapor by representing its content.

Both contain liquids of much higher quality than those found inside the column. The liquid levels inside the drums are adjusted to maintain and ensure the continuous availability of these liquid holdups.

II.6.3. Liquid–vapor contactors

The liquid–vapor contactor is one of the components of a distillation apparatus which receives two sources: the rising vapor and the descending liquid. This opposing movement is known as countercurrent diffusion. It offers the interfacial area for exchange between the two phases and facilitates the mass and heat transfer between the liquid and vapor phases.

The contact occurs through various active contact elements to generate the mass transfer between the phases.

II.6.4. Heads

The distillation column contains two heads which are the top head and the bottom head. They are made of the same metal as the column shell in various shapes most often elliptical and semispherical. The heads are fixed to the shell by welding; however, bolted flanges are used to secure the top head in some cases and for diameters that are less than 1.5 m.

With identical strength and diameters, the thickness of spherical heads is less than that of elliptical heads [13].

II.7. General characteristics of distillation column

II.7.1. Retention

The retention is defined as the volume of the liquid per unit volume of the column. It presents a key parameter which separates the components efficiently and precisely in batch distillation.

There are two types of retention, the sum of which represents the total retention. The first type is one is static retention in addition to dynamic retention that is during operation.

II.7.2. Efficiency

For column with packing, it measures the separation quality; while, in plate column it is defined as the ratio of the number of theoretical plates to the number of reel plates.

Some variables can affect efficiency, including [14]:

- The liquid's viscosity.
- Vapor velocity in the liquid.
- Relative volatility of the constituents.
- Liquid flow path length on the tray.

II.7.3. Fineness

For a distillation column, an increase in fineness corresponds to a reduced retention volume.

Fineness enables columns with identical efficiency and separation capacity to be compared.

II.7.4. Flow rate

The volume of the vapor that is passing through the column per unit of time represents the flow rate which depends on the column diameter.

Exceeding it a certain limit may cause some problems in the column such as flooding, When the vapor prevents the liquid from returning to the reboiler, a liquid plug is formed.

In the column, Both the liquid and vapor have the same molar flow rate.

II.7.5. Duty

The column duty can be characterized by two different definitions .It represents the theoretical number of plates and the height equivalent to a theoretical Plate HETP. Its value can change considerably according to operating conditions [13].

II.8. Types of columns

II.8.1. Trays column

The trays play an important role in the distillation column by exploitation the gaseous phase's pressure energy to ensure its dispersion inside the liquid.

The trays play an important role in the distillation column. The operating principle of these trays is based on the exploitation of the gaseous phase's pressure energy to ensure its dispersion inside the liquid [15].

They present a set of horizontal plates placed on top of each other, with a specific distance left between each tray. The distance is precisely determined to avoid operational problems [16].

II.8.1.1. Trays types

II.8.1.1.1. Bubble cap trays

This type is characterized by the bubble cap which is installed vertically on the tray. Where the cap outlets are serrated in order to increase the contact surface between the phases [15].

They were constructed of cast iron with all its weight, but thanks to stamped steel caps it became lighter.

Bubble cap trays are the predominant type used in petroleum and chemicals industries [13].

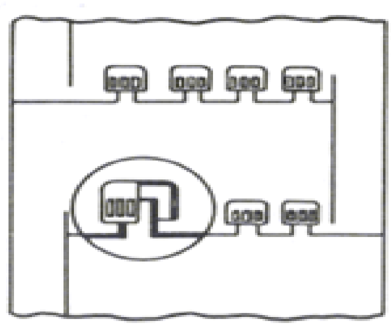

Figure II.4: Bubble cap tray [14].

II.8.1.1.2. Sieve trays

In this type, the liquid layer is traversed vertically by the vapor. This tray performances well only when the flow rate deviates minimally around the optimal design value. Therefore, despite its low cost, it did not achieve great success. It is considered as one of the oldest trays [13].

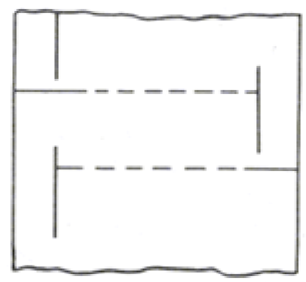

Figure II.5: Sieve tray [14].

II.8.1.1.3. Valve trays

The valve tray is perforated tray which contains valves in its perforations. The vapor flow rate escaping horizontally into the liquid determines the lift height of the valves. Depending on the need and according to the flow rate, it is possible to the valve.

This type of trays is a trade-off between the bubble cap tray and the Sieve tray [13].

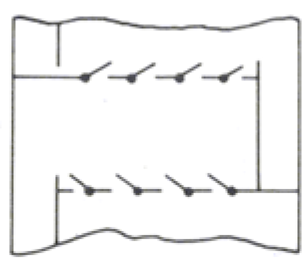

Figure II.6: Valve tray [14].

II.8.1.1.4. Uniflux trays

In comparison with the types described above, the vapor dispersion in this type is less homogeneous.

The tray consists on S-shaped strips, allowing the steam escapes through the notches unidirectionally towards the downstream weir; thereby, making the flow of the liquid over the tray easier. This type is a modified version of the bubble cap tray [13].

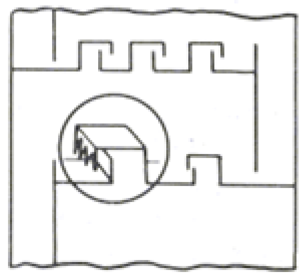

Figure II.7: Uniflux tray [14].

II.8.1.1.5. Jet trays

This tray works on directing the steam escape under the valves in the aim of minimizing the liquid gradient.

The design of the jet tray follows the same principles of simplicity and low cost used in the perforated tray [13].

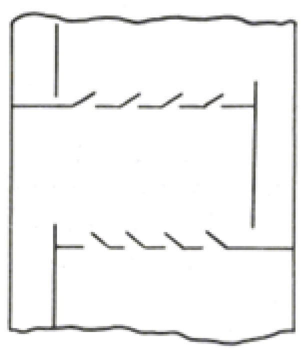

Figure II.8: Jet tray [14].

II.8.1.1.6. Trays without Weir

These trays are distinguished by their low manufacturing cost.

The counter-currently flowing of the liquid and the vapor through the same orifices, the entire allows the entire to be treated as a packed column [13].

II.8.2. Packed columns

The packing columns ensure a large interfacial area between the vapor phase and liquid phase. As a result, Unlike the stagewise countercurrent flow of vapor and returning liquid, in packing column the flow is truly countercurrent.

For small diameters, building a tray column which operates occurs several stages is costly, that is why packed columns are favored [17].

Two principal types of packing exist:

- Structured packing.
- Random packing.

The raw material for producing these types is building materials such as metals, plastics, ceramics and polymers.

II.8.2.1. Structured packing

Structured packing consists of corrugated metal sheets where the size of the corrugation is in the range of 0.5 to 2 cm or of wire mesh. These packing materials are arranged vertically in the column in the form of assembled layers blocks, note that the size of the blocks is generally 25 cm.

The common materials of the structured packing are: Flexipac, Mellapak, Gempak, BX…

II.8.2.2. Random packing

The random packings are made of discrete structural elements randomly dumped into the column, where the random packing size varies between 1 and 10 cm.

The random packings are porous solids with multiple geometries including coils, mesh, cylinders and spheres.

The main materials of this packing type are: Pall rings, IMTP, Hiflow, Raschig rings … [18].

II.9. Heat exchange equipment

II.9.1. Reboiler

The operating principle of the reboilers is based on two basic mechanisms of rotation which are the natural circulation of a fluid or by forced circulation of the fluid to be reboiled.

Producing a stripping vapor stream to the column and supplying a heat source for the system are the two main objectives of utilizing reboilers.

Three main types exist [19]:

- The kettle type reboiler. (The most used)
- The once through thermosyphon reboiler.
- The re-circulating thermosyphon reboiler.

II.9.1.1. The kettle type reboiler

The kettle type reboiler is composed of a tube bundle enclosed within a large shell, with the heating medium flowing through the tube. The liquid to be reboiled is introduced to the shell's bottom, exactly at the end adjacent to the tube inlet/outlet chamber. After the liquid's boiling, it partially evaporates via flowing across the tube bundle.

In order to achieve partial separation between liquid and vapor, sufficient space must be provided over the tube bundle and the top of the shell when determining the casing diameter.

The liquid level above the tube bundle is determined by a baffle weir which is installed at the end of the bundle. the vapor produced is allowed to exit from the top of the shell through one or two nozzles. The boiling liquid flows over the weir to the shell outlet nozzle were. Below the weir a space is designed to accommodate for liquid holdup to satisfy the surge requirements for the product. As a result, his obviates the need to providing space in the bottom of the tower for product surge [19].

The uses of this type are numerous because it supports a diverse variety of vaporization loads.

II.9.1.2. The once through thermosyphon reboiler

This type of reboilers is used when large relatively quantities of surge is needed for the bottom and in cases necessitating the provision of head for the product pump.

II.9.1.3. The re-circulating thermosyphon reboiler

In terms of its method of operation, this type is analogous similar to the once through thermosyphon reboiler.

It utilized in cases of vaporization rates higher than 60% of reboiler feed is required and a kettle reboiler is unsuitable.

II.9.2. The condenser

The condenser is a heat exchanger that condenses vapors into liquids.

A cold process stream or water are used to cool the vapor through heat exchange; as a result, the condensation occurs.

In condensers, there are three mechanisms, that must be taken into account during the rating procedure, as each mechanism is addressed separately and across different pre-selected sections of the condenser.

The three mechanisms are [19]:

- The resistance to heat transfer of the condensing film.
- The resistance to heat transfer of the vapor cooling.
- The resistance to heat transfer of the condensate film cooling.

There are three types of condensers namely:

- Total condenser.
- Partiel condenser.

II.9.2.1. Total condenser

After the exit of the vapor flow from the column, it enters the condenser where it comes into contact with a cooler medium and condenses.

The condensed liquid is drawn by a pump into two flows: primary and secondary.

This type is characterized by its converting to all the vapor into liquid.

II.9.2.2. Partial condenser

The partial condenser converts only fifty percent of the vapor into a distillate, while the remaining vapor is sent for further processing.

It serves to route all the condensed liquid to the top tray of the column and to operate as an external top tray for the column [11].

II.10. Conclusion

In this chapter, we learned about the distillation process in the petroleum industry, its principles, and its various types, in addition to describing the most important stages and the resulting products.

We also discussed the distillation column and highlighted its important role within distillation units, its types, and its components.

One of the serious problems that can be encountered with the distillation column will be addressed in the next chapter.

Chapter III:

Technical study of trays collapse

III.1. Introduction

The good performance of the distillation column which is the basis of any atmospheric distillation unit is related to the safety of its internal components, especially trays that facilitate the contact between rising vapor and descending liquid.

Over the years, a frequent technical problem is encountered at the level of the distillation column C1 in the atmospheric distillation unit which is the damage with the collapse of the trays, one of the serious problems encountered by the unit that had negative effects such as reduced separation efficiency and increased maintenance costs.

Therefore, identifying and analyzing the main causes of this problem, studying their technical implications and proposing corrective measures is an essential step to prevent this problem from happening again and ensure the column safety and the separation efficiency, as addressed in this chapter.

III.2. The atmospheric distillation column C1

The atmospheric distillation column C1 plays a key role in the unit by fractionating crude oil. It consists of 52 trays with a height of 50.55 meters divided into three zones as follows:

- The flash zone: includes trays 5 and 6, where the heated crude enters from above tray 5.
- The enrichment zone: that includes trays 6 to 52, with a diameter of 8.1m.
- The stripping zone: that includes trays 1 to 5, with a diameter of 3,8m.

The tray number 17 was removed, leaving a total of 51 trays.

The trays from 15 to 45 were replaced with new ones, while the trays from 1 to 15 and 46 to 52 remained unchanged.

The column C1 has three side draws: Kerosene (Kero), Light Gas Oil (LGO) and Heavy Gas Oil (HGO) all of which drawn through side strippers [3].

The column also has a two circulating refluxes which are the top pump around and the bottom pump around in order to heat recovery from the column. The tower can also be divided into the following circuits [3]:

- Overhead Circuit.
- Top Pump Around Circuit.
- Kerosene Circuit.
- LGO Circuit.
- HGO Circuit.
- Bottom Pump Around.
- RCO Circuit.

III.3. The operating conditions of the column

The following table presents the operating conditions of the column, including temperature, pressure, and flow rate which based on data collected from the control room.

TableIII.1: Operating conditions of the column C1.

Charge flow rate	1334 m^3/h
Top column temperature	164.1 °C
Top column pressure	1.239 kg/cm^2
Bottom column temperature	335.2 °C
Bottom column pressure	1.661 kg/cm^2

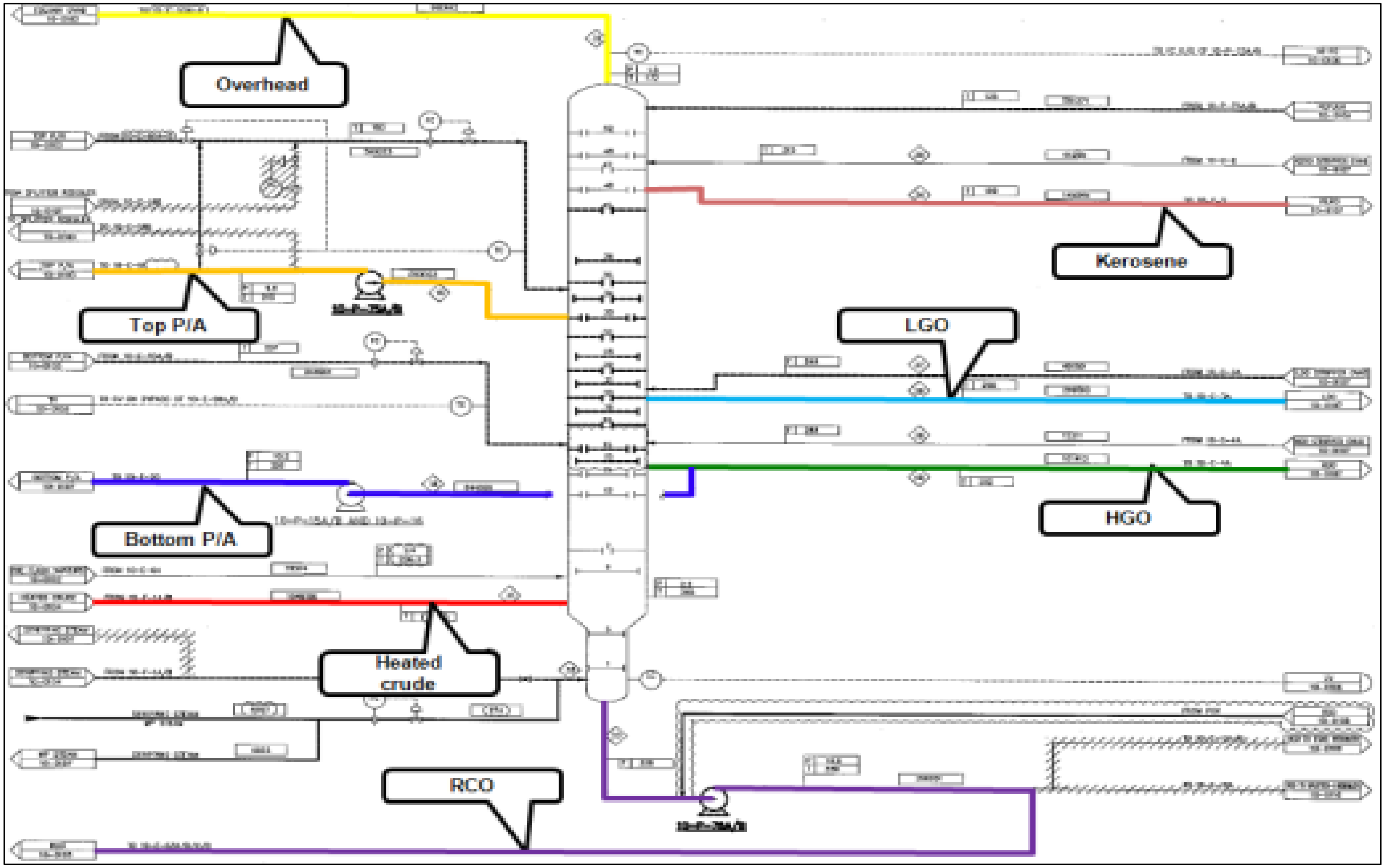

Figure III.1: Diagram of the atmospheric column C1[3].

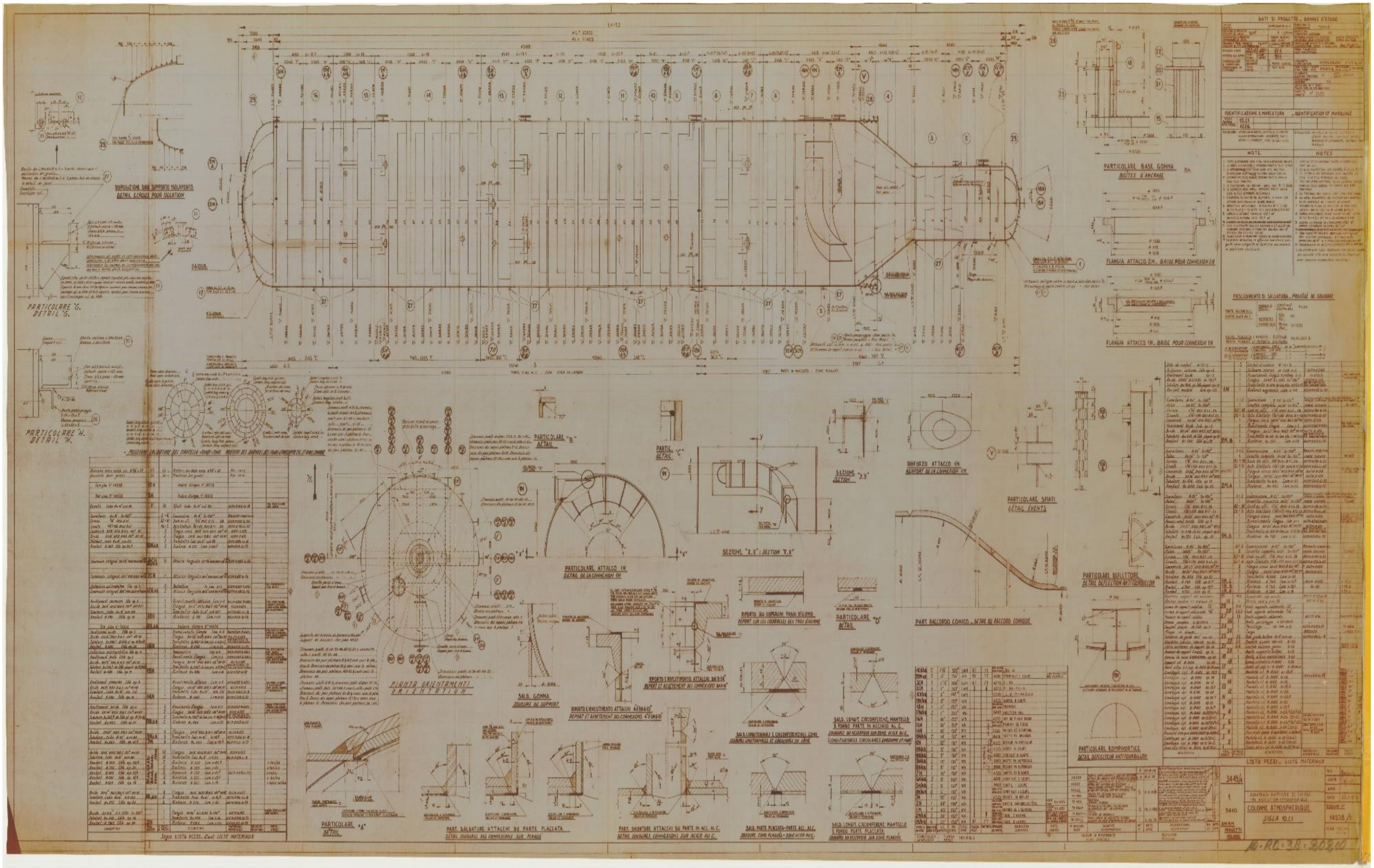

Figure III.2: Technical Drawing of the atmospheric distillation column C1.

III.4. The history of the column C1

Based on available maintenance reports, a history of f the most significant malfunctions and interventions carried out over the past twenty years has been compiled.

The table below represents the most significant events related to the column trays and the corrective work carried out to prevent each problem.

Table III.2: The history of tray-related problems.

Date	Problem	Corrective Measures
07/2004	-Not specified in the report.	-Repair and straightening of trays.
06/2006	-Not specified in the report.	-Repair and straightening of trays.
06/2008	-Not specified in the report.	-Repair and straightening of the platforms from the 1st to the 5th.
12/2012	-Valves detachment: from the tray number 52 to the 46th. -Tray 48: the two NH3 injection systems are sheared. -Three elements of the tray number 47, located on the EAST side, are perforated at the NH3 injection systems.	-Replacement of the first five trays in the flash zone. - Replacement of 250 valves on the various trays. - Manual cleaning of the spillway basins. - Replacement with an identical NH3 injection system, tag number 17 N A/B according to drawing No. 14551 / 2. - Replacement in kind of the perforated elements on tray 47.

05/2016	-Flash zone: trays collapsed on all five levels. -Deformed and blackened trays. -1st MH (lower bottom): cracked welds on the stainless steel cladding in some places, slight deposit on the first five trays falling to the bottom of the column. -3rd MH: valves detachment. -4th MH: detachment of the valves (approximately 300). -Final MH: blackened tray surfaces.	-Replacement of 5 trays in the flash zone. - Replacement of valves on the different trays. - Water flushing of the column. - Complete descaling of the column bottom up to the flash zone and NDT inspection.
04/2017	-Flash zone: trays collapsed on all five levels. -Deformed trays. -1st MH (lower bottom): cracked welds on the stainless steel cladding in some places, slight deposit on the first five trays falling to the bottom of the column. -3rd MH: valves detachment. -4th MH: detachment of the valves (approximately 300). -Final MH: blackened tray surfaces.	-Replacement of 5 trays in the flash zone. - Replacement of missing valves on the different trays. - Water flushing of the column. - Complete descaling of the column bottom up to the flash zone and NDT inspection.
05/2024	-Collapse of 5 trays. -Valves detachment.	-Reassembly of the trays and valves. -Repair by welding.

	-Advanced corrosion. -Deformed and cracked internal wall	
05/2024	-Flash zone: trays collapsed on all five levels -Deformed and blackened trays -1st MH (lower bottom): cracked welds on the stainless steel cladding in some places, slight deposit on the first five trays falling to the bottom of the column. -2nd MH: - trays detachment -3rd MH: valves detachment -4th MH: detachment of the valves (approximately 300). -Final M H: blackened tray surfaces, a perforated area on tray 47, detachment of the valves (Approximately 200).	- Repair and straightening of 5 trays in the flash zone - Valves replacement on the different trays. - Water flushing of the column. - Measurement of shell thicknesses - Repair of the perforated area on the tray number 47 - Welding repair of cracks on the flash zone deflector

III.5. Analysis of the causes

This analysis aims to understand how the causes identified during our internship in the atmospheric distillation unit affected the trays and led to their collapse.

The causes are mentioned in the figure below:

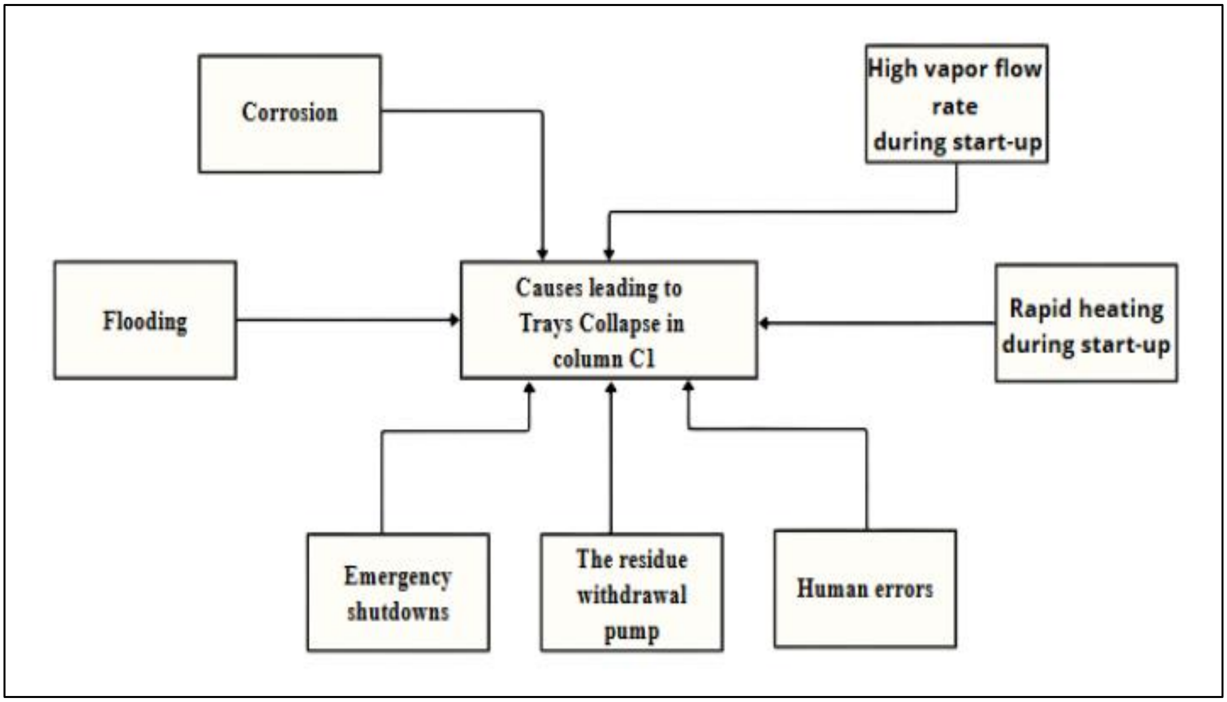

Figure III.3: The main causes of trays collapse in the column C1.

III .5.1. Corrosion

Corrosion is defined as the destructive attack that metals are subjected to through a chemical or electrochemical reaction with their environment [20]. This causes a measurable change in the metal, and may lead to its deterioration or loss of its mechanical properties under the direct influence of the surrounding environment [21].

III .5.1.1. Corrosion in distillation column

Corrosion is one of the critical problems that refining industries have suffered from since ancient times. In the case of the distillation column, the condensate water resulting from the condensation of the residual moisture in dehydrated crude oil with injected steam for improving heat transfer due to the low temperature during the decomposition of products inside the column provides a suitable hydrochemical environment for corrosion.

The petroleum entering the column contains complex compounds containing chlorine, sulfur, and nitrogen. At high temperatures, reactions occur, producing other compounds such as hydrogen chloride (HCl), hydrogen sulfide (H_2S) and ammonia (NH_3). These resulting substances are the main cause of corrosion. When they come into contact with the metal in the presence of condensed water, they attack it and causing corrosion in the trays, plates, and other column components.

HCl reacts with NH_3 via crystallization reaction producing ammonium chloride (NH4Cl) in the form of solid particles that can be deposited on the metallic surface of the column forming a deposits that favors under-deposit corrosion phenomena [22].

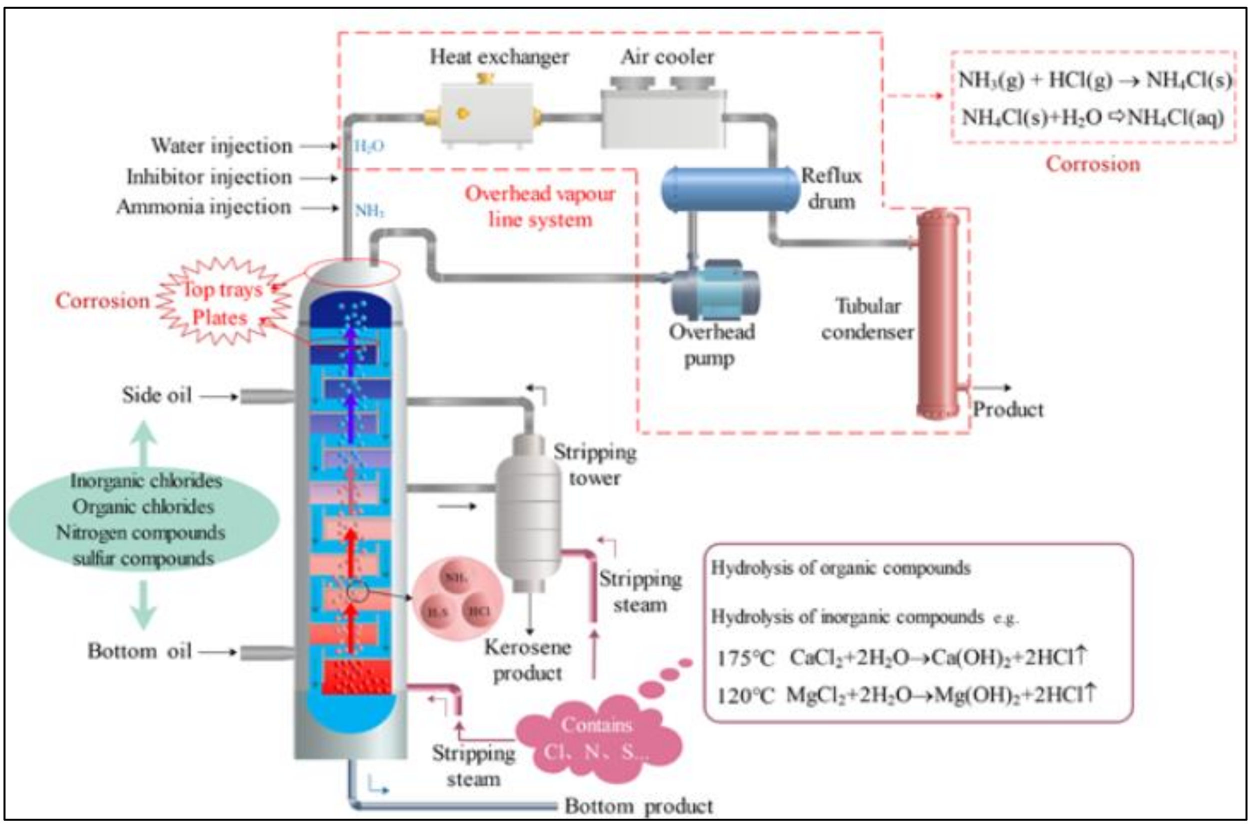

Figure III.4: The process of crude oil distillation and the location of corrosion in a distillation column [22].

III.5.1.2. The analysis

In the studied column C1, we find that corrosion has direct consequences for the trays.

When solid deposits accumulate on the tray surface, specifically in the valves, they block them and create an obstruction that prevents the normal flow of rising steam. This increases pressure drop and pressure, creating overpressure under the trays and reducing the hydraulic balance within the column.

The tray decks and the supports affected by corrosion lose thickness over time, decreasing their mechanical resistance and load-bearing capacity. Under overpressure, they are subjected to significant mechanical stresses that lead to deformation. This leads to further weakening of the tray, causing it to partially detach from its position after losing its ability to bear load and pressure. Consequently, a tearing phenomenon occurs, contributing to the collapse experienced in column C1, which represents an advanced failure related to all the aforementioned factors.

FigureIII.5: Tray thinning.

Figure III.6: Tray support corrosion.

Figure III.7: perforated tray due to corrosion

Figure III.8: corroded trays after their collapse.

III.5.2. High vapor flow rate during the start-up

During start-up, the vapor injection through pipes to ensure the sparging of the crude oil is an important step that facilitates its evaporation in the column's trays [23].

III.5.2.1. The analysis

A sudden increase in the vapor flow can generate a hydrodynamic shock, inducing hydrodynamic forces within the column. These forces act on the column's internal components particularly the trays and their supports. The generated forces may be unevenly distributed and concentrated in certain zones. This situation can cause local deformations such as tilting or buckling of certain parts of the tray.

Under the effect of the high steam flow rate, the valves rise to accommodate the steam, changing their initial position and causing instability that generates vibrations. These vibrations increase the mechanical stresses on the trays, causing them to tire.

Excessive steam flow rate can also induce flooding, where fluid accumulates on the trays, creating a mechanical load.

Under the combined effect of vibrations, forces and the flooding load, the load-bearing capacity of the supports decreases, leading to mechanical failures. These failures cause instability and imbalance, which can gradually develop until reaching a critical threshold, beyond which the structure can no longer support the applied loads, thus causing the trays to collapse.

Therefore, a high vapor flow rate can be considered as a potential cause of trays collapses.

As part of operational feedback, the unit has two steam pipes which are LS and MS.

The unit normally operates at LS, but when the MS was used in a previous operation in 2017, it led to the collapse of 17 trays in addition to the deformation of some other trays. This historical case confirms the previous analysis.

Figure III.9: The state of the C1 trays after a high vapor flow rate that caused their collapse.

Figure III.10: C1 supports after a high vapor flow rate.

III.5.3. Flooding

Flooding is a serious phenomenon that affects distillation columns which occurs when the liquid level reaches a point where it cannot be properly drained, resulting in liquid accumulation and the inability to move down due to the velocity of the vapor [10][24].

III.5.3.1. Analysis

Under normal operating conditions, the liquid level is in the flash zone which is located between trays five and six. In this case, there is a balance between the vapor and the liquid states, resulting in heat exchange and a uniform temperature distribution.

In some cases, the liquid level rises above the previous two trays and may even reach higher levels and this is related to the phenomenon of flooding which creates thermal imbalances that lead to poor evaporation and liquid accumulation. This accumulation creates a load that causes mechanical problems, weakening the trays' load-bearing capacity and potentially causing them to collapse.

Figure III.11: deformed trays**.**

III.5.4. Rapid heating during start-up

III.5.4.1. The analysis

Rapid heating during start-up, characterized by excessively high temperatures is a major cause of tray collapse, especially below and in the flash zone. This is due to the thermal shock generated in the column components including the trays, resulting from non-uniform expansion. This creates significant internal stresses, deformation, and loosening, all of which lead to tray instability and, in advanced cases, their collapse. Furthermore, the high temperature increases the evaporation rate, raising the velocity of the vapor phase. This turbulence leads to pressure increases in various parts of the column, potentially affecting and deforming specific areas or displacing valves.

As part of operational feedback, during the unit's start-up after a shutdown, a rapid heating was performed which leads to the appearance of a cavitation phenomenon at the level of the kerosene withdrawal pump. Upon inspection, it was found that the filter was clogged by several valves from the trays.

This scenario reinforces the idea that rapid heating can play a decisive role in damaging the trays Starting with their valves then their collapse in the advanced stages of failure.

III.5.5. Emergency shutdowns

Emergency shutdowns are a fundamental safety procedure for any facility. They involve quickly halting a process to prevent a problem from escalating or worsening, with the aim of protecting personnel and the facility and preventing any environmental impact resulting from an incident in the process [25].

III.5.5.1. The analysis

Among the operational disruptions that the unit may encounter, affecting the efficiency and safety of the equipment, are sudden or emergency shutdowns, which are resorted to in the event of various malfunctions. These shutdowns lead to a rapid and sudden change in the column's normal operating conditions of pressure, temperature, and flow rates, after the column had been operating in a thermally and mechanically stable state. Repeated restarts-up after each shutdown lead to thermal, mechanical, and pressure-related stresses.

For example, sudden cooling after heating leads to expansion and contraction of the metal trays due to thermal shock. Sudden pressure changes lead to vibrations. Hydrodynamic instability results in instability in steam quantity and disruptions in feed distribution. During shutdowns, water, salts, and hydrochloric acid accumulate and upon the start-up, the reaction between them is strong, leading to a rapid corrosion. All these factors combined lead to tray fatigue which according to inspection reports, had previously been repaired and welded.

Considering the aging of these trays, emergency shutdowns are an aggravating and triggering factor of buckling and deterioration for the trays that are already in a poor mechanical condition and consequently, collapse will occur.

The table below represents the unit's recorded shutdowns over the last 5 years, showing their frequency, their various causes and durations, and the accompanying frequent start-ups.

Table III.3: History of the unit's shutdowns.

Date	Cause of shutdown	Duration	Startup date

31/07/2021	Shutdown due to a power outage.	24h	01/07/2021
14/09/2021	Shutdown due to lack of cooling water (supply interruption by ADE)	2days	16/09/2022
13/01/2022	General shutdown	8days	21/01/2022
20/02/2022	Shutdown following port consignment (high Fuel BTS stock), used to eliminate a leak on aero 11MEA1/12.	24h	21/02/2022
20/04/2022	Shutdown to eliminate a water leak at the line 20	2days	22/04/2022
02/07/2022	Shutdown for intervention, extraction and threading of the tube bundles of the 11E78G/H heat exchanger pair	2days	04/07/2022
17/10/2022	Shutdown to eliminate a leak on the furnace 11-F1A in the radiation zone	3days	20/10/2022
05/11/2022	Shutdown following the shutdown of the control consoles, due to an electrical failure on UPS1	20h	06/11/2022
22/01/2023 A 20 :00h	General shutdown of all affected areas (HC leak at 11-V-8)	03days	25/01/2023
26/04/2023	Naphtha C leak at 11-EA-7A	1day	27/04/2023
01/07/2023	Scheduled shutdown of the unit	12days	12/07/2023
10/08/2023	Shutdown due to the presence of white smoke at GM of 11-MP-72B.	12h	11/08/2023

10/01/2024	Shutdown due to a leak of HC at 11-EA-1/12 (10-EA-1/5)	18h	11/01/2024
02/05/2024	Arrêt programmé de l'unité	29days	31/05/2024
23/09/2024	A shutdown caused by a voltage drop	06h	23/09/2024
07/10/2024	Shutdown due to a leak of HC at 11-MEA-1-9	24h	08/10/2024
30/10/2024	Shutdown due to a leak of HC at 11-MEA-1-23.	24h	31/10/2024
17/02/2025	HC leak at the 11-EA-1/8 level	2days	19/02/2025
25/02/2025	HC leak at 11-EA-1/5 and 11-EA-1/4	2days	27/02/2025
23/03/2025	Shutdown due to a power outage.	07h	23/03/2026
09/08/2025	Shutdown due to maintenance work	3days	12/08/2025
12/10/2025	Shutdown due to the blockage of the impulse lines 11-FIC-2F /11-FI-2F1	13h	13/10/2025
08/11/2025	HC leak at the 11-MEA-1/8 level	1day	09/11/2025
10/01/2026	Shutdown due to a high fuel storage	3days	13/01/2026
21/01/2026	Shutdown due to a high fuel storage	2days	23/01/2026
08/02/2026	Shutdown due to a blockage in the capillary line on the 11-FT-52 flow transmitter.	08h	08/02/2026
31/03/26	Shutdown due to a high fuel storage	6days	05/04/2026

III.5.6. The residue withdrawal pump

III.5.6.1. The analysis

The decrease in the liquid level which is the atmospheric residue can lead to the malfunction of the lower pump that is responsible for drawing I t. Although there is a protection system that stops the pump when the level drops to a certain level (8%), approaching this limit can cause serious disturbances within the column specifically in the lower section. This makes the trays below the flash zone susceptible to instability and vibration especially considering their increased vulnerability to thermal stress due to the high temperatures in this section

In addition to their aging and previous exposure to collapse incidents. Consequently, the likelihood of their collapse due to the unstable operation of the residue withdrawal pump at low level conditions increases.

III.5.7. Human errors

III.5.7.1. The analysis

Human errors are one of the reasons for tray collapses, particularly errors in maintenance and installation. According to statements from unit workers, some trays were found to be secured with far too few screws compared to what is required for proper mechanical fastening. This makes them unable to withstand vibrations and forces resulting from the aforementioned causes, leading to their detachment and eventual collapse.

Furthermore, repairs relying on welding are also a contributing factor, as weld areas are weak points in the structure and create significant stress concentrations that gradually lead to collapse.

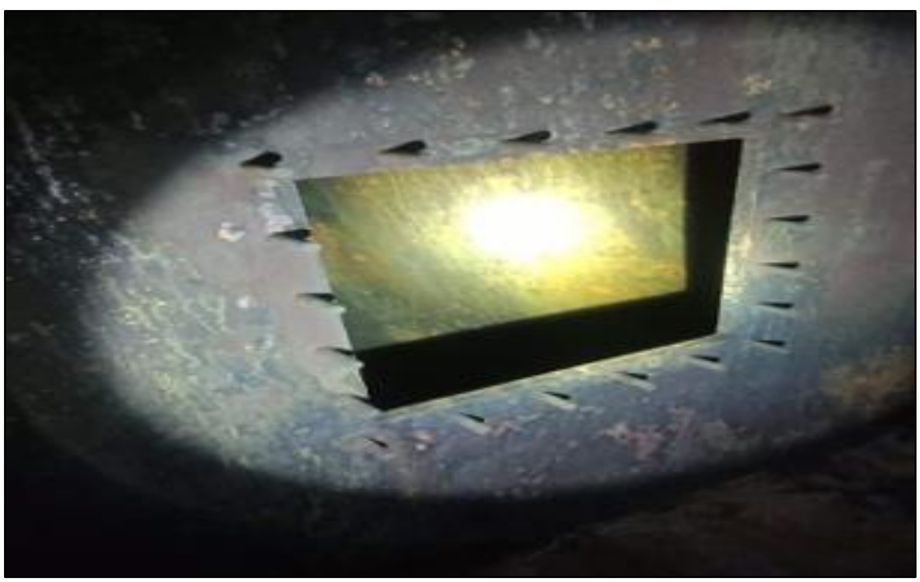

Figure III.12: Bottom Manway of the column C1.

III.6. Bow-tie method

The bow tie is a risk analysis method that combines a fault tree and an event tree around a single feared event. Its main advantage is that it provides a concise tree structure offering a comprehensive view of all potential accident sequences. In hazard studies conducted by industrial facilities subject to ICPE regulations, this method has become virtually indispensable for addressing the most critical accident scenarios [26].

III.6.1.Bow tie construction

Table III.4: Components of the Bo- tie method [27].

The component	**The description**
Hazard	A situation capable of causing harm
Top Event	The 'release' of hazard
Threat	A possible cause which may trigger a hazard, resulting in a top event.
Preventive Barrier	A preventive measure to prevent the release of a threat
Recovery Measure	A preparatory measure to recover from or mitigate risks in the event of an incident, or a measure to reduce the severity of its consequences.
Consequence	Condition/event(s) resulting from the release of hazard / top

III.6.2. Bow-tie objectives

The objectives of the Bow-tie method are the following [27]:

- Represent the relationships between hazards, their causes and their effects.
- Evaluate the contribution of each cause and the severity of each risk.
- Position prevention and protection barriers; Evaluate the aggravating factors that reduce the effectiveness of the barriers.
- Evaluate the robustness and contribution of the barriers to risk mitigation.
- Evaluate the impact of these barriers on the overall risk rating.

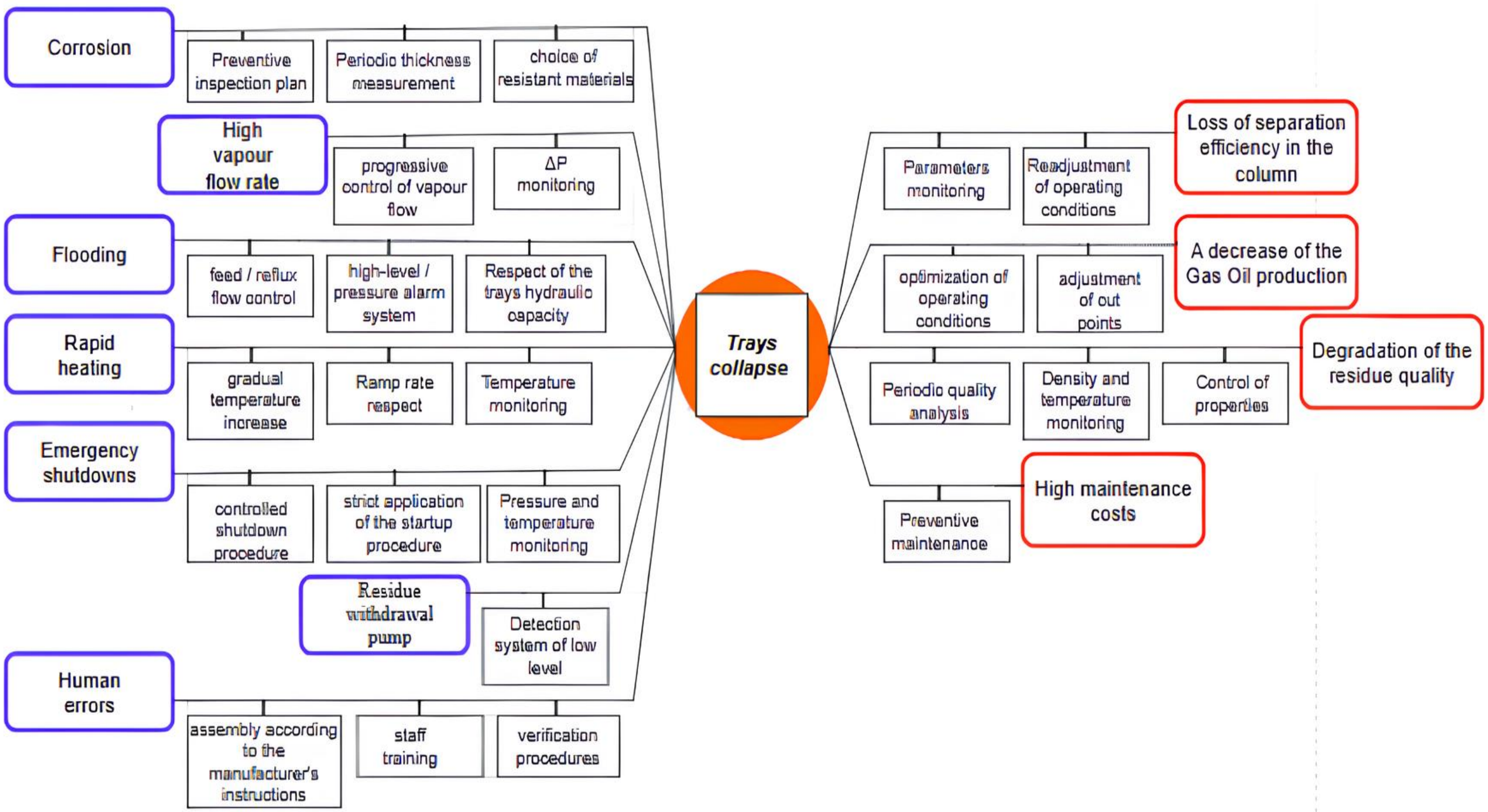

Figure III.13: The bow tie diagram of trays collapse in the column C1.

III.6.3. The description of the Bow-tie diagram

The diagram above represents the Bow-tie method, one of the most powerful tools for industrial risk analysis. It was used to study the phenomenon of trays collapse in the atmospheric column C1 in order to analyze the various contributing factors and highlighting its impact on the column and the unit as a whole.

The left side connects potential causes with preventative barriers designed to avoid this problem and reduce its likelihood of development, while the right side connects the resulting consequences with protective barriers that mitigate the impact and repercussions of these consequences. This analysis relies on the top event, which is the trays collapse in this study, placed in the center of the diagram as a separator between the causes and the consequences.

To facilitate reading the diagram, a color coding was used as shown in the table.

Table III.5: color coding of the Bow-tie diagram.

The color	Its meaning
Orange	Top event
Blue	Main causes
Red	Main consequences
Black	Preventive and protective barriers

III.6.4. Key findings from the analysis

The most important points that the analysis revealed are the following:

- The causes of collapse are multiple, including mechanical, operational, and human factors.
- The start-up stage is considered the most critical period, as rapid variations in steam, temperature and flow conditions increase the likelihood of tray collapse
- Collapse does not necessarily shutdown the unit but directly impacts the efficiency and effectiveness of the separation process.
- Monitoring operational variables plays a crucial role in mitigating the escalation of disturbances.

- The collapse leads to the high costs of maintenance and necessary interventions.
- Preventive and protective barriers play an important role in reducing the development of the collapse problems.

III.6.5. Measures to control and reduce the risk of trays collapse

To mitigate this phenomenon and prevent its recurrence, we focused on a set of measures targeting the root causes of this problem. Among the most important of these are strengthening inspection and monitoring procedures through periodic inspection of the trays, measuring thickness, and monitoring corrosion. In addition to enhancing monitoring and early detection systems to track pressure differences, temperature, flow rates, and liquid levels to detect any disturbances or deviations from the design operating conditions, thus providing sufficient time for intervention before the situation worsens; controlling operating conditions, especially during startup and shutdown phases, through gradual control of steam flow and adherence to the heating rate and strengthening the role of human intervention by training workers on proper operating, startup, shutdown, and maintenance procedures, in addition to verification and review after installation. All of this aims to control this phenomenon, reduce its recurrence, contribute to improving column performance, maintain product quality and ensure the stability of the entire unit.

III.6.6. Role of preventive and protective barriers

The table represents the objective of each barrier shown in the analysis.

Table III.6: Role of preventive and protective barriers

The barrier	Its role
Preventive inspection plan	Early detection of corrosion areas before the situation worsens
Periodic thickness measurement	Monitoring the impact and the rate of corrosion
Choice of resistant materials	Extending the lifespan of the trays and reducing the likelihood of mechanical weakness

ΔP monitoring	Early detection of hydraulic shocks or the onset of the flooding phenomenon
Progressive control of vapor flow	Reducing operational shocks during start-up
High-level / pressure alarm system	Prediction and rapid intervention before the problem develops
Respect of the trays hydraulic capacity	Avoid overloading the trays beyond their design capacity.
gradual temperature increase	Reducing sudden thermal stress
Ramp rate respect	Ensuring uniform and gradual heating
Strict application of the startup procedure	Ensuring stable operating conditions after restart
Detection system of low level	Prevent pump operation under unstable conditions
Staff training	Improving workers efficiency and reducing operational errors
Verification procedures	Detecting errors before they affect the integrity of the column
Parameters monitoring	Monitoring column performance and detecting any disruptions
Optimization of operating conditions	Recovering part of the separation efficiency
Periodic quality analysis	Detection of deterioration in residue properties
Control of properties	Maintaining the product within acceptable operating limits
Preventive maintenance	Reducing breakdowns and heavy interventions through early detection

This analysis allowed us to better understand the phenomenon of trays collapse and provide a comprehensive overview of its various causes and consequences. It emphasized the role of barriers and stressed the importance of continuous monitoring of operating conditions, adherence to maintenance procedures, and early diagnosis to guarantee the stability and efficiency of the column.

III.7. Conclusion

This chapter examines the phenomenon of trays collapse on the column C1 by analyzing the various factors that contribute to this phenomenon and how they affect the trays, relying on operational and historical data from previous incidents on the column thereby contributing to a better understanding of the collapse phenomenon.

Furthermore, the study is supported by the Bow-tie methodology, which helps to highlight the relationship between the causes and the consequences, identify preventative and protective barriers and determine the role of each in improving operating conditions and reducing the recurrence of tray collapse in the future.

Chapter IV:

Economic study of trays collapse

IV.1. Introduction

The phenomenon of trays collapse is one of the most critical problems, which although it does not cause a complete shutdown of the unit, leads to numerous operational disruptions and affects the separation efficiency and the column throughput.

This technical malfunction is accompanied by several economic impacts, most notably the costs of maintenance and repairs resulting from the collapse, aimed at restoring the trays to their proper condition. Furthermore, it leads to a decrease in the output of some valuable products.

This chapter aims to study the economic impact of trays collapse in the column C1 and analyze the associated costs, both direct and indirect, to confirm the seriousness of this malfunction.

IV.2. Direct costs

IV.2.1. Maintenance costs

The occurrence of a collapse problem necessitates various inspection and maintenance operations depending on the extent of the damage. These operations require human, technical, and material resources, resulting in direct maintenance costs.

After assessing the extent of the damage and its effects by opening the column and conducting an internal inspection, which allows for examining the condition of the trays and identifying those that have collapsed or are damaged, the appropriate interventions are determined.

In some cases, Corrective actions may be limited to reinstalling the trays while in others, the damaged trays are first re-equipped and returned to their original condition. In this context, new trays are not usually purchased; rather, the existing trays within the unit are utilized. Welding and strengthening work is carried out, fastening points are addressed, and the mechanical stability of the column's internal structure is restored, ensuring its continued operation as required.

All these interventions require specialized maintenance personnel, in addition to the use of appropriate lifting, securing, and welding equipment. They also necessitate a considerable amount of time for preparation and execution, especially in cases where the damage is more severe, which increases the complexity of the intervention process and requires meticulous planning of the maintenance steps. Thus, the problem is not limited to the operational aspect only, but also leads to direct maintenance costs that can become high with repeated occurrences.

IV.2.2. Estimation of potential costs for replacing the trays

The collapse of the trays could cause such significant damage that routine maintenance would be insufficient to restore the necessary operational efficiency, especially considering the age of the trays and previous frequent repairs. This might necessitate tray replacement to ensure stable operation and efficient separation.

The replacement process requires technical equipment, installation work, and the cost of procuring new trays, etc. These costs increase depending on the number of trays to be replaced, the dimensions of the column, and the nature of the required interventions.

Therefore, estimating the potential costs and economic burdens associated with replacement operations is a crucial step in highlighting the approximate extent of losses and costs related to the collapse, and consequently, its economic impact and repercussions on the unit.

To estimate these costs, the simplified economic correlation proposed by Enríquez-Gutiérrez et al. (2015) was adopted [28]. This model was originally developed by Bravo (1997) [29] and later updated by Enríquez-Gutiérrez et al. using the Chemical Engineering Plant Cost Index (CEPCI) to account for inflation effects [30]. The original correlation is expressed as follows:

$$\$\ \boldsymbol{Cost_{HPT}} = [\mathbf{11}.\boldsymbol{D}^{\mathbf{2}}(\mathbf{52}\boldsymbol{N_t} + \mathbf{160})]\ \boldsymbol{F_i}.\boldsymbol{F_R}$$

where:

- **D**: The diameter of the column (m).
- $\mathbf{N_t}$: Number of trays.
- $\mathbf{F_i}$: Installation factor.
- $\mathbf{F_R}$: Removal factor.

According to Enríquez-Gutiérrez et al. (2015) [28], the original Bravo (1997) correlation was based on CEPCI = 386.5 [29]. The authors updated the correlation using CEPCI = 687.9 for 2013.

More recently, several techno-economic studies reported a CEPCI value of 798.6 for 2024 [31–33]. In addition, Chemical Engineering reported that the average CEPCI in 2025 was approximately 1.6% higher than in 2024 and that the first months of 2026 continued an upward trend [34]. Based on these observations, the CEPCI value for 2026 was estimated as follows:

$$CEPCI_{2025} = 798.6 \times (1 + 0.016) = 811.38$$

The January 2026 preliminary CEPCI was reported to be 6.8% higher than the corresponding value of the previous year, indicating that inflationary pressures on equipment and construction costs continued into 2026 [35]:

$$CEPCI_{2026} = 811.38 \times (1 + 0.068) = 866.55$$

The escalation factor relative to the original 1997 basis is therefore:

$$Escalation\ factor = \frac{CEPCI_{2026}}{CEPCI_{1997}}$$

$$Escalation\ factor = \frac{866.55}{386.5} = 2.242$$

The original correlation can therefore be updated to 2026 conditions by multiplying the coefficient 11 by the escalation factor:

$$11 \times 2.242 = 24.66$$

Thus, the updated tray replacement cost correlation becomes:

$$\$\ \boldsymbol{Cost_{HPT,2026}} = \mathbf{24.66} \times \boldsymbol{D}^2 \times (\mathbf{52} \times \boldsymbol{N_t} + \mathbf{160}) \times \boldsymbol{F_i} \times \boldsymbol{F_R}$$

For high-performance trays, Enríquez-Gutiérrez et al. (2015) recommend [28]:

- $F_i = 1.4$
- $F_R = 0.1$

Since the column diameter varies between sections, the replacement cost was calculated separately for each section.

Table IV.1: Estimation calculation results.

Zone	Stripping section	Enrichment section
Column diameter (m)	3.8	8.1
Number of trays	5	46
Equation	$24.66 \times (3.8)^2 \times (52 \times 5 + 160) \times 1.4 \times 0.1$	$24.66 \times (8.1)^2 \times (52 \times 46 + 160) \times 1.4 \times 0.1$
Cost	20938,12 $	578058,53 $

$$\$\ Cost_{total} = Cost_1 + Cost_2$$

$$\$\ Cost_{total} = 20938{,}12 + 578058{,}53$$

$$Cost\_total = 598996{,}65\ \$$$

The obtained results indicate that tray replacement represents a significant economic burden, particularly in large-diameter sections containing a large number of trays. The estimated costs include not only the procurement of new trays but also the expenses associated with removal and installation operations.

It is worth noting that the initial replacement cost estimate obtained using the original Bravo (1997) correlation was 267192.341 $. After updating the correlation to 2026 economic conditions using the Chemical Engineering Plant Cost Index (CEPCI), the estimated replacement cost increased to 598996,65 $. This represents an increase by a factor of approximately 2.13, reflecting the significant escalation of equipment and installation costs over the period 1997–2026. The magnitude of this increase is consistent with the evolution of the CEPCI, which rose from 386.5 in 1997 to an estimated value of approximately 824 in 2026.

It should be emphasized that these values provide only a preliminary estimate based on simplified correlations available in the literature. Actual industrial costs may differ depending on tray design, construction materials, labor costs, shutdown duration, contractor quotations, and sitespecific conditions. Nevertheless, the calculations clearly demonstrate the potentially substantial economic impact associated with tray collapse and highlight the importance of maintaining tray integrity and preventing mechanical failures.

IV.2.3. Costs related to the technical interventions

Interventions can be categorized into costs as shown in the table.

Table IV.2: Technical interventions and associated costs.

The technical intervention	**The cost**
Intervention during programmed shutdown	Costs associated with increased maintenance workload
Reconditioning the damaged trays	Repair and rehabilitation costs
Reinstalling the trays	Mechanical intervention costs
Welding and reinforcement work	Maintenance equipment and work costs
Checking the supports and fixation points	Technical monitoring costs
Use of lifting, dismantling and installation equipment	Logistical and technical costs

We observe from the classification that maintenance operations are not limited to technical interventions only, but also include the costs of equipment, logistics, etc. Although interventions are carried out during scheduled shutdowns, trays collapse leads to an increase in the volume of work, complicates operations, and raises costs.

IV.3. Indirect costs

IV.3.1. Reduction in Gas Oil production

The Gas Oil is one of the most important products of the distillation process which is used in many energy and industrial sectors. It also presents a product of considerable economic value within refinery output stream as it is a product that can be valued and marketed.

Among the consequences of the tray collapse problem is the impact on the effectiveness of the contact between the liquid and vapor phases, thus reducing the efficiency of separation and recovery of various petroleum fractions.

In this context, and based on the data recorded before and after the collapse phenomenon at the atmospheric distillation column C1 a decrease in the flow rate of the Heavy Gas Oil (HGO) was observed following to the collapse.

According to data taken from the unit, the column produces the HGO at a flow rate of approximately 76 m^3/h under normal operating conditions. To illustrate the effect of the collapse, the table below shows the varying values of HGO at different times during one of the days when a tray collapse incident occurred in column C1.

Table IV.3: Evolution of HGO flow rate over time during a period of trays collapse.

Time (h)	**Flow rate (m^3/h)**
00:00	55.0
01:00	62.7
02:00	56.8
03:00	59.3
04:00	66.2
05:00	60.9
06:00	60.1
07:00	58.4
08:00	57.5
09:00	57.3
10:00	58.9
11:00	59.8
12:00	58
13:00	56.4
14:00	57
15:00	59.6

16:00	63.2
17:00	61.7
18:00	61.0
19:00	63.1
20:00	62.8
21:00	65.1
22:00	65.1
23:00	62.6

The table shows a clear decrease in the flow rate of HGO during the study day compared to normal conditions, with values ranging from 55 as the lowest value to 66.2 as the highest value. These values confirm that the trays collapse reflects a decrease in the separation efficiency within column C1.

The risk of this decline in output increases when considering the role this product plays in covering a significant portion of national consumption, as it is one of the petroleum products that is consistently in demand in the local market. Any decrease resulting from the collapse will lead to a reduction in the quantity allocated for consumption and market supply. If this decline continues, it will become difficult to meet the needs of the local market, especially during periods of high demand or increased consumption.

Therefore, maintaining its production at the required level is a crucial step to ensure a degree of self-sufficiency in meeting national needs related to energy, transportation, and various industrial uses as well as maintaining the unit's sustainable economic performance and the stability of its contribution to the national market.

In addition to the above, the continuation of this type of problem may place additional pressure on other production units to compensate for the recorded shortfall and this could negatively impact overall economic performance due to increased operational costs.

Even if the collapse does not cause the unit to shut down, it has a significant economic impact in the medium and long term even gradually or indirectly.

IV.3.1. The impact on the atmospheric residue production

The atmospheric residue is the heavy fraction remaining at the bottom of the column after the distillation process and the separation of the lighter distillates. It possesses specific physical properties.

The residue is a product suitable for industrial exploitation and valorization; therefore, maintaining their required properties within operational limits is crucial. The collapse phenomenon encountered by column C1 affected not only the quantity of HGO but also the quantity and properties of the residue.

Operational data recorded at the unit during the period when the trays collapse on the column C1 showed an increase in the quantity of the residue and a change in its properties, particularly flash point and density, which became closer to the properties of the crude oil.

This change indicates that the column lost some of its separation efficiency, leading to the transfer of some of the compounds that should have been separated in the lighter distillates into the residual due to performance disturbances caused by the trays falling. Thus, the increase in its quantity does not reflect an improvement in production but rather a decrease in efficiency.

From an economic standpoint, the increased quantity of the atmospheric residue due to the trays collapse does not translate into greater profitability, as this increase is accompanied by a reduction in lighter more valuable and highly demanded products than the residue.

The continuation of operation under these types of disruptions, reduces the overall economic profitability of the unit. Furthermore, producing this with undesirable characteristics may necessitate additional processing or negatively impact the quality of industrial operations.

Within the context of new and upgraded refining projects, we note the hydrocracking project which is currently under construction. This project utilizes low-value heavy products as feedstock to convert them into lighter, more economically valuable derivatives.

The characteristics of the feedstock are a crucial factor in the unit's effectiveness, ensuring conversion efficiency and the quality of the final products. The deterioration of the residue properties resulting from the trays collapse incident makes it less compatible with operational requirements, impacting its suitability for use in this type of unit. This limits its valorization efficiency and negatively impacts the expected economic return of the product.

Consequently, the impact of trays collapse can also affect future processing opportunities for heavy products, particularly given the trend towards developing high-value deep conversion units.

IV.4. Conclusion

This economic study revealed that the collapse phenomenon affecting the column C1 was not limited to the technical aspect alone, but also had several serious economic repercussions. It led to increased maintenance costs due to repeated interventions, in addition to the potential costs incurred if the trays had to be replaced instead of relying on current repair methods. Furthermore, it impacted the Gas Oil production, contributing to difficulties in meeting national market needs, and altered the characteristics of the atmospheric residue. Therefore, controlling the trays collapse phenomenon and minimizing its recurrence is crucial for ensuring the unit's economic efficiency.

General conclusion

General conclusion

This work addresses the phenomenon of tray collapse, a major problem encountered by the C1 atmospheric distillation unit at the Skikda RA1K refinery, which affects separation efficiency and unit stability.

Our study enabled us to identify the potential causes of tray collapse and understand how each contributes to the damage. This was achieved by relying on operational data from the unit and historical data from previously recorded incident inspection reports. Among these causes were corrosion, high steam flow rate and rapid heating during the startup, flooding, emergency shutdowns, residue withdrawal pump and human errors.

We also highlighted the most significant consequences of this malfunction. Although it does not lead to unit shutdown, it significantly impacts separation efficiency and column product quality. To link causes and consequences, we employed the Bow-tie method, which identified several necessary actions to mitigate the development and recurrence of this malfunction.

Our study also examined the direct and indirect economic repercussions of this phenomenon, such as maintenance and repair costs, reduced yield of heavy gas oil which is a valuable and in-demand product in the national market, increased residue production and changes in its properties to become more similar to crude oil.

Although tray replacement is not usually carried out at the unit level, our economic study focused on estimating the cost of tray replacement to highlight the potential economic impact of the worsening trays collapse phenomenon and to provide an approximate picture of the financial burdens the unit may face in the future, especially considering the age of the trays and their frequent need for repairs, making replacement an unavoidable necessity in the future.

Ultimately, studying tray failure remains of paramount importance due to its multiple impacts on operations and production and this study is a part of efforts to improve industrial performance inside the unit.

The findings of the research provide a wide array of future avenues for research on phenomena associated with tray collapse in crude distillation columns:

- Hydraulic evaluations of the column C1 should occur to estimate the effects of operating conditions—specifically, vapor velocity, liquid loading, and pressure drop—upon tray stability and collapse mechanisms.
- Future research should also examine the role of corrosion upon tray failure through metallurgical studies and measurements of thickness to better define the relationship of material deterioration and structural failure.
- Develop a quantitative risk assessment of tray collapse by estimating the probability of occurrence of the identified causes and by examining existing preventative and protective measures.
- Extend the economic assessment by incorporating production losses, maintenance time for repairs, excessive energy penalties incurred while repairing, and degradation in product quality.

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