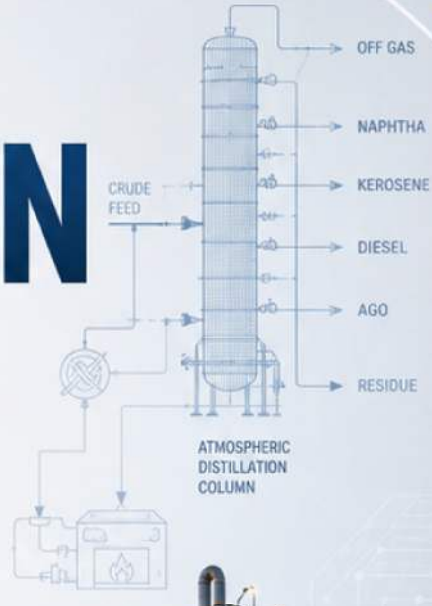
CRUDE DISTILLATION UNIT (CDU) OPTIMIZATION



Strategies, Technologies & Best Practices for Refinery Performance

YIELD IMPROVEMENT

ENERGY EFFICIENCY

OPERATING COST REDUCTION

RELIABILITY & AVAILABILITY

EMISSIONS REDUCTION

PROCESS ENGINEERING REFERENCE

2026

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1. Introduction

1.1 Purpose and Scope of This Guide

This guide is intended to support process engineers, refinery technologists, APC engineers, analyzer specialists, reliability engineers, and project teams in identifying, prioritizing, and implementing CDU optimization opportunities.

The guide focuses on practical engineering actions that can improve CDU energy efficiency, desalter performance, product quality control, cut-point optimization, preheat train reliability, crude flexibility, corrosion risk management, and readiness for APC, digital twin and AI-based optimization.

The scope covers both operational improvements and capital project opportunities. It does not replace detailed refinery-specific process simulation, HAZOP, SIL review, mechanical design, or site-specific engineering assessment. Instead, it provides a structured framework for evaluating optimization opportunities and defining the measurement, control and digital infrastructure required to capture them.

1.2 Intended Users

This guide is intended for the following users:

User Group	Main Use of the Guide
Process Engineers	Identify CDU constraints, improvement opportunities and optimization priorities
Operations Teams	Understand operating variables, APC targets and abnormal condition responses
APC Engineers	Define controlled variables, manipulated variables, constraints and model maintenance needs
Analyzer Engineers	Define analyzer locations, measurement requirements and sample system requirements
Reliability / Inspection Teams	Link fouling, corrosion and equipment limits to optimization decisions
Planning / Scheduling Teams	Connect crude selection, crude switching and LP optimization with real-time CDU constraints
Project Managers	Build phased implementation plans and investment justification
Management	Evaluate ROI, risk reduction and strategic value of CDU optimization initiatives

2. CDU Process Overview

The Crude Distillation Unit (CDU), also referred to as the Atmospheric Distillation Unit (ADU), is the first and most critical processing step in any petroleum refinery. Every barrel of crude oil entering a refinery must pass through the CDU before downstream conversion units can further process it into marketable products. As such, the CDU is often called the "heartbeat" of the refinery — if the CDU stops, the entire plant stops.

CDU optimization is not a single action but a continuous, multi-disciplinary effort that spans process engineering, mechanical integrity, advanced control, digitalization, and commercial strategy. It directly determines a refinery's energy intensity, product yield, environmental footprint, and ultimately, its profitability.

Key Fact
A modern CDU processing 100,000 BPD (barrels per day) consumes roughly 25–40 MW of fired heat. A 4% improvement in thermal efficiency can translate to savings exceeding USD 1.5 million per year, with payback periods commonly below 3 years.

Understanding the core process is a prerequisite to any optimization effort. The CDU separates crude oil into distinct boiling-range fractions (cuts) through fractional distillation at near-atmospheric pressure. The unit typically consists of four major subsystems: the preheat train, the desalter, the fired furnace (heater), and the main fractionation column with associated strippers and pumparounds.

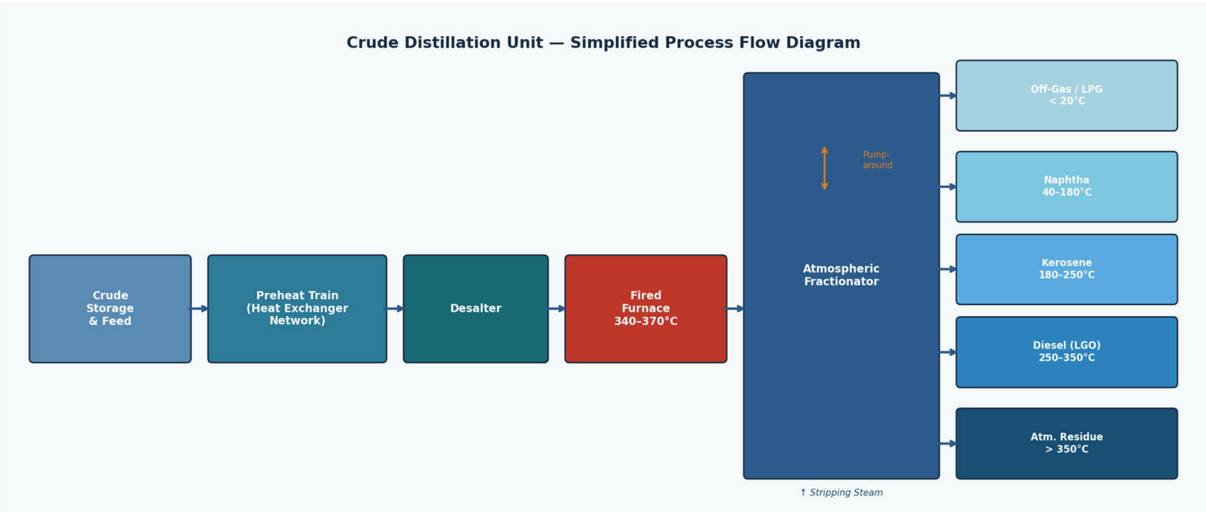

Figure 1: Simplified Crude Distillation Unit Process Flow Diagram — crude oil passes through the preheat train, desalter, and fired furnace before entering the atmospheric fractionator, which separates it into multiple product streams.

2.1 Preheat Train

Cold crude feed (typically 30–50°C) enters a series of shell-and-tube heat exchangers that recover heat from hot product streams and pumparounds leaving the fractionator. A well-designed preheat train recovers 60–70% of the total energy demand of the CDU, raising the crude temperature to 220–

280°C before it enters the furnace. Fouling of heat exchanger tubes is the single greatest threat to preheat train performance and is discussed in detail in Section 5.

2.2 Desalter

At 120–150°C, the crude enters the desalter, where wash water is mixed into the stream and an electrostatic field causes brine droplets to coalesce and separate by gravity. This removes chloride salts (sodium, calcium, and magnesium chlorides) that would otherwise hydrolyze in the furnace to form hydrochloric acid (HCl), causing catastrophic overhead corrosion in the fractionator. Target desalter efficiency is typically >95% salt removal.

The chemistry behind this corrosion risk is well defined. Raw crude can carry chloride salt loadings as high as 2,000 PTB (pounds per thousand barrels); refinery practice demands this be reduced to below 5 PTB before the crude reaches the furnace. At elevated temperatures, metal chlorides hydrolyze to generate hydrogen chloride (HCl) gas:

$MgCl_2 + 2H_2O \rightarrow Mg(OH)_2 + 2HCl$ *[onset ~120°C]*

$CaCl_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HCl$ *[onset ~200°C]*

$NaCl + H_2O \rightarrow NaOH + HCl$ *[onset ≥500°C]*

Critically, conventional desalters remove inorganic chloride salts but are ineffective against organic chlorides — chlorinated solvents, chemical treatment residues, and transportation contaminants that can enter the refinery in the crude stream. These organic species decompose at furnace temperatures to liberate HCl independently of desalter performance. This distinction, explored further in Section 5.5, is the basis for the emerging practice of measuring Total Chlorine (in addition to salt content) as a crude acceptance and corrosion risk metric.

2.3 Fired Furnace

The desalted crude is raised to its transfer temperature — typically 340–370°C — in a fired heater (radiant-convective box furnace). The furnace is the single largest energy consumer in the CDU and is limited to ~380°C to prevent thermal cracking and coke formation inside the radiant tubes. Furnace optimization focuses on maximizing thermal efficiency (typically 88–92%), minimizing excess air, and monitoring tube skin temperatures to prevent hot spots.

2.4 Engineering Variables and Constraints Summary

The following table summarizes the main CDU subsystems, key engineering variables and typical constraints that must be considered during optimization.

CDU Subsystem	Key Variables	Typical Constraints
Preheat Train	Furnace inlet temperature, exchanger U-values, pressure drop, crude flow split	Fouling, hydraulic limits, exchanger metallurgy, tube velocity
Desalter	Inlet salt, outlet salt, wash water rate, interface level, demulsifier dosage	Emulsion stability, brine carryover, water handling capacity, transformer limits

Fired Furnace	Outlet temperature, bridgewall temperature, excess O_2, draft, tube skin temperature	Tube metallurgy, coking risk, maximum firing duty, emissions limits
Atmospheric Column	Pressure, draw rates, pumparound duties, stripping steam, cut points	Flooding, weeping, product specifications, heat balance
Product Draws	Distillation curve, flash point, density, cetane, smoke point, RVP	Off-spec risk, quality give-away, downstream unit requirements
Overhead System	Chloride load, pH, corrosion rate, neutralizer dosage	HCl formation, ammonium chloride deposition, corrosion limits

2.5 Atmospheric Fractionator & Products

The hot feed enters the flash zone of the fractionation column, where vapors rise and condense on valve or sieve trays according to their boiling points. Stripping steam injected at the column base lowers the partial pressure of light components, improving the recovery of diesel from the residue. The table below summarizes the typical product fractions produced by the CDU.

Fraction	Boiling Point Range	API Gravity	Primary Use
Off-Gas / LPG	< 20°C	N/A	Refinery fuel, cooking gas
Naphtha / Gasoline	40–180°C	55–90	Gasoline blending, petrochemicals
Kerosene / Jet Fuel	180–250°C	40–55	Aviation fuel (Jet A-1)
Light Gas Oil (Diesel)	250–350°C	28–40	Road transport diesel
Atmospheric Residue	> 350°C	< 20	Vacuum unit feed, asphalt, bunker

Table 1: CDU Product Fractions — boiling point ranges are indicative and adjusted by cut point control.

2.6 CDU Optimization KPI Dashboard

The document contains many valuable figures and economic indicators, including furnace duty, FIT improvement, APC savings, energy reduction, CO_2 reduction, and payback figures.
Add a dedicated KPI table near the beginning of the guide:

KPI	Typical Target / Monitoring Purpose
Furnace Inlet Temperature	Maximize within exchanger and crude constraints
Furnace Outlet Temperature	Maintain required transfer temperature without cracking
Furnace excess O_2	Optimize combustion efficiency
Desalter salt removal efficiency	Maintain >95% removal where applicable
Desalter outlet salt	Prevent corrosion and fouling
Product cut-point deviation	Minimize quality give-away
Product off-spec events	Reduce through APC and online analyzers
Heat exchanger U-value	Detect fouling and cleaning need
Pressure drop across exchangers	Detect fouling, restriction, or hydraulic limits
Energy intensity	Fuel consumption per barrel processed
CO_2 emissions	Linked to furnace fuel and steam consumption
APC service factor	Measure controller usage and effectiveness

2.7 Minimum Measurement Architecture

- Crude feed flow, temperature, pressure
- Preheat train inlet/outlet temperatures
- Exchanger pressure drops
- Desalter inlet/outlet salt measurement
- Water content / BS&W
- Desalter interface level
- Wash water flow and quality
- Furnace bridgewall temperature
- Furnace excess O_2
- Furnace draft
- Tube skin temperature
- Column pressure profile
- Product draw temperatures
- Online NIR for naphtha, kerosene, diesel, AGO/HGO
- Product density and distillation estimators
- Total Chlorine for corrosion risk
- Corrosion monitoring in overhead system

3. Optimization Strategy Framework

CDU optimization can be structured across three time horizons: real-time (seconds to hours), short-term (days to weeks), and long-term (months to years, typically tied to turnarounds and capital investment). Effective refineries coordinate all three levels simultaneously, using a cascade of models from online process simulators to refinery-wide linear programming (LP) planners.

Time Horizon	Optimization Lever	Enabling Tool
Real-Time (seconds–hours)	Set-point control, product quality, cut-point adjustment	DCS, APC (MPC), online analyzers (NIR/GC)
Short-Term (days–weeks)	Crude blending, preheat routing, exchanger cleaning schedule	Process simulation, scheduling tools, data analytics
Long-Term (months–years)	HEN retrofit, column internals upgrade, debottlenecking	Rigorous simulation (Aspen HYSYS/PROII), capital planning

Table 2: CDU Optimization Time Horizons and Enabling Tools

CDU optimization maturity can be evaluated using five levels:

Level	Description
Level 1 — Manual Operation	Operation relies mainly on operator experience and laboratory data
Level 2 — Basic Monitoring	Key process variables are trended, but limited online quality feedback is available
Level 3 — Analyzer-Based Control	Online salt, product quality and crude property analyzers are connected to DCS/APC
Level 4 — APC / Digital Twin Integration	APC and digital twin models use reconciled online data for optimization
Level 5 — AI-Assisted Optimization	AI models generate economic set-point recommendations and predictive maintenance actions

The target for most refineries should be Level 3 as a minimum and Level 4–5 for high-value crude flexibility and margin optimization.

4. Preheat Train & Heat Exchanger Network Optimization

The crude preheat train is the most energy-intensive subsystem of the CDU and represents the greatest opportunity for thermodynamic improvement. Its performance is measured by the Furnace Inlet Temperature (FIT) — the higher the FIT, the less supplementary fuel the fired heater must burn.

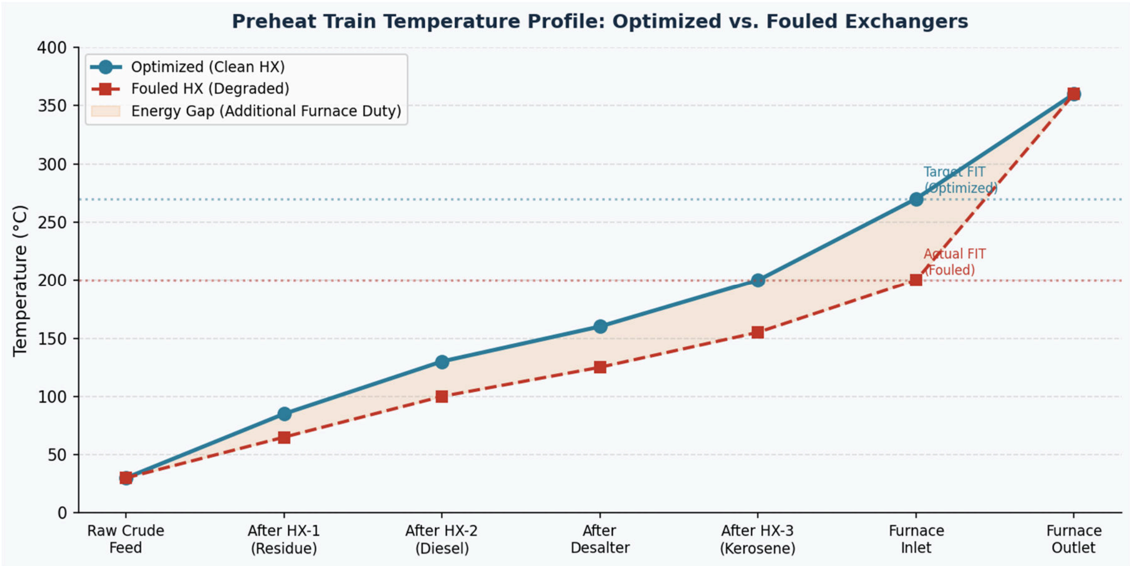

Figure 2: Preheat Train Temperature Profiles — an optimized (clean) preheat network achieves a furnace inlet temperature (FIT) of ~270°C, while fouled heat exchangers may reduce this to ~200°C, forcing the furnace to burn 20–30% more fuel.

4.1 Heat Integration Pinch Analysis

Pinch technology (Linnhoff analysis) identifies the minimum thermodynamic hot and cold utility requirements of the CDU and reveals where additional heat recovery exchangers should be placed to close the gap. Modern implementations use equation-oriented software platforms (such as Aspen Energy Analyzer or HTRI Xchanger Suite) that simultaneously optimize the heat exchanger network (HEN) topology, flow routing, and individual exchanger sizing.

A key metric is the Heat Recovery Approach Temperature (HRAT) — the minimum temperature difference at the pinch. Lowering the HRAT improves energy recovery but increases capital cost (larger exchangers), so the optimal HRAT is determined by a cost-benefit trade-off.

4.2 Preheat Train Engineering Checklist

The following checklist should be used during preheat train optimization studies:

- Confirm furnace inlet temperature baseline and seasonal variation.
- Calculate U-value for each major exchanger.
- Trend pressure drop across each exchanger.
- Identify exchangers with abnormal fouling rate.
- Compare current heat recovery against clean-design performance.

- Check crude flow distribution across parallel exchanger banks.
- Evaluate crude compatibility before crude switching.
- Review desalter performance as a possible fouling root cause.
- Estimate fuel penalty caused by reduced furnace inlet temperature.
- Optimize cleaning schedule based on economic penalty, not fixed calendar intervals.
- Confirm metallurgy and tube velocity limits before changing routing.
- Check whether additional exchangers or HEN retrofit are justified.

4.3 Furnace Energy Penalty Calculation

A reduction in furnace inlet temperature increases fired heater duty and fuel consumption. The additional energy duty can be estimated as:

Additional duty = crude flow rate × heat capacity × reduction in furnace inlet temperature

This calculation should be converted into:

- additional fuel consumption;
- additional fuel cost;
- additional CO_2 emissions;
- reduced throughput if the furnace reaches duty limitation.

This calculation is essential for justifying exchanger cleaning, antifoulant treatment, desalter improvement or heat exchanger network retrofit.

4.4 Fouling Management

Heat exchanger fouling is the primary cause of preheat train performance degradation. In the CDU context, fouling arises from multiple mechanisms: asphaltene precipitation, inorganic salt deposition (particularly downstream of an underperforming desalter), corrosion product buildup, and biological growth. Key management strategies include:

- Online monitoring: Continuous tracking of the overall heat transfer coefficient (U-value) and pressure drop for each exchanger identifies fouling in real time.
- Predictive cleaning scheduling: Optimization algorithms determine the economically optimal cleaning frequency, balancing lost production from shutdowns against the energy penalty of fouled exchangers.
- Chemical treatment: Injection of dispersant and antifoulant chemicals into the crude stream can extend run lengths between mechanical cleans.
- Crude pre-treatment: Improved desalter operation (correct wash water rate, electrostatic field strength, and demulsifier dosing) prevents the single most common fouling initiator — salt carryover.
- Exchanger metallurgy and tube geometry: Twisted-tube or helical-baffle designs reduce fouling deposition rates by creating turbulent flow regimes that inhibit stagnant boundary layers.

4.5 Crude Flow Routing Optimization

When the preheat network contains parallel exchanger trains or bypass valves, the optimal distribution of crude flow among the parallel paths is a non-trivial mathematical problem. Constrained thermohydraulic optimization models can solve for the flow split that maximizes the final crude temperature subject to pressure drop, heat duty, and metallurgical constraints. Refineries implementing automated flow routing optimization have reported FIT improvements of 15–35°C versus heuristic operator practice.

5. Advanced Process Control (APC)

Advanced Process Control, most commonly implemented as Model Predictive Control (MPC), is the single highest-return optimization investment available to a CDU operator. Industry surveys consistently place the economic benefit of a well-maintained APC application in the range of USD 0.05–0.20 per barrel processed, primarily through tighter product quality control, increased throughput, and reduced energy consumption.

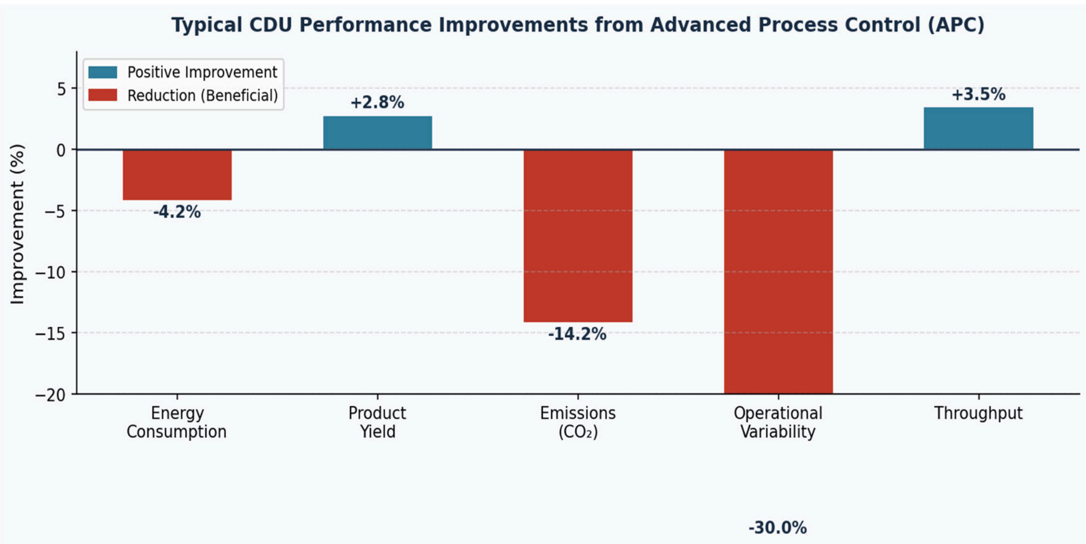

Figure 3: Typical CDU Performance Improvements from APC Implementation — note that reductions in energy consumption and emissions are beneficial even though shown as negative percentages.

5.1 How MPC Works in the CDU Context

A CDU MPC controller simultaneously manipulates multiple controlled variables (CVs) — product draw rates, pumparound duties, stripping steam flows, furnace firing rate — to maintain dozens of controlled process variables within their target ranges. Unlike single-loop PID controllers, MPC predicts the future dynamic response of the process over a horizon of 20–60 minutes and pre-compensates for measured disturbances (e.g., crude feed rate changes or crude composition shifts) before they impact product quality.

Key controlled variables in a CDU MPC application typically include:

- Naphtha/kerosene and kerosene/diesel cut-point temperatures (D86 boiling points, estimated by online NIR or gas chromatograph).
- Atmospheric residue 95% boiling point (controlled via furnace outlet temperature and stripping steam rate).
- Column pressure and overhead receiver level.
- Pumparound return temperatures and duties.
- Furnace pass flow balance and tube outlet temperatures.

5.2 Online Property Estimators

The effectiveness of APC is directly dependent on the quality of product property feedback. Online analyzers — particularly Fourier Transform Near-Infrared (NIR) spectrometers — provide continuous, multi-stream, multi-property measurements (flash point, density, distillation curve) at cycle times of 1–3 minutes, compared to 1–4 hours for laboratory GC analysis. Rigorous first-principles inferential models ("soft sensors") calibrated against the online analyzer data can further improve real-time estimates of unmeasured properties.

5.2.1 Analyzer Placement on the CDU

A standard CDU online analyzer installation covers two measurement families. Salt-in-crude electrometric analyzers (ASTM D3230) are positioned at three points in the desalter circuit (S1–S3). A single NIR spectrometer with an optical multiplexer serves five product draw streams (N1–N5) simultaneously:

Point	Location	Measurement	Control Action
S1	Crude inlet header	Incoming crude salt content (PTB)	Crude scheduling & purchasing decisions
S2	Desalter inlet	Salt loading to desalter	Feed-forward: wash water & demulsifier rate
S3	Desalter outlet	Desalter removal efficiency	Feedback: closed-loop desalter performance control
N1–N2	Naphtha streams	D86 T90, RVP, PIONA	Stabiliser / splitter cut-point APC
N3	Kerosene / jet fuel	T50, T90, flash point, smoke point	Kerosene/diesel cut-point optimisation
N4	Diesel / LGO	T90, cetane index, density	Diesel draw rate & product value maximisation
N5	AGO / HGO	T95, viscosity, flash point	FCCU feed quality gate

The effectiveness of any online analyzer investment hinges on a simple comparison: laboratory methods return a result 4–8 hours after sampling — by which time the crude batch has already transited the desalter and entered the furnace. Pipeline batch interfaces, tank transitions, and marine cargo blends can shift salt content by hundreds of PTB within one to two hours. The laboratory result describes crude that no longer exists in the system and cannot be fed to an APC controller operating on a 1–5 minute cycle.

Online analyzers eliminate this latency entirely. A fast-loop sample conditioning system delivers a representative process sample to the analyzer cell within 30–90 seconds of being drawn from the main line; the analyzer returns a calibrated result every 1–5 minutes and writes it directly to the DCS historian via OPC-UA or Modbus, where it is immediately available as an APC feedback variable.

5.2.2 Process NIR Analyzer Property Prediction

A single Process NIR Analyzer can simultaneously predict the following product quality parameters with laboratory-equivalent accuracy, using chemometric (partial least-squares regression) models calibrated against laboratory reference data:

5.3 Documented APC Benefits

A landmark case study applying the Honeywell Profit Controller to a CDU/VDU-4 unit reported the following improvements over conventional PID control:

- 4.0% reduction in overall CDU energy consumption.
- 14.2% reduction in CO_2-equivalent emissions.
- 30% reduction in product quality variability (standard deviation of key product specifications).
- Net annual savings of USD 1.61 million, with a capital investment of USD 3.78 million and a payback period of 2.35 years.

5.4 APC Readiness Checklist

Before implementing or reactivating CDU APC, the following items should be verified:

- Online product quality measurements are available and reliable.
- Product quality models are validated against laboratory data.
- Key constraints are correctly configured in the MPC controller.
- Manipulated variables are available in automatic mode.
- Operators understand APC objectives and constraint handling.
- APC service factor is measured and reviewed regularly.
- Furnace, column and product quality constraints are included.
- Crude feed changes are detected and used as measured disturbances.
- Analyzer response time is suitable for APC use.
- APC model maintenance procedure is defined.
- Benefit tracking methodology is agreed before commissioning.

5.5 Minimum Instrumentation for CDU Optimization

A practical CDU optimization program requires a reliable measurement foundation. The following measurement architecture is recommended:

Essential Measurements

- Crude feed flow, temperature and pressure
- Furnace inlet and outlet temperature
- Furnace fuel gas flow

- Furnace excess O_2 and draft
- Column pressure and key tray temperatures
- Product draw flow rates and temperatures
- Desalter interface level
- Wash water flow
- Demulsifier injection rate
- Product laboratory quality data

Recommended Online Analyzer Measurements

- Salt-in-crude at crude inlet or desalter inlet
- Salt-in-crude at desalter outlet
- Online NIR Analyzer for naphtha, kerosene, diesel and gas oil streams
- Product density
- Flash point / distillation property prediction
- Water / BS&W measurement where applicable

Advanced Optimization Measurements

- Total Chlorine in crude
- Online crude characterization: API gravity, density, sulfur, viscosity, TAN and water
- Corrosion monitoring in the overhead system
- Tube skin temperature monitoring
- Exchanger U-value and pressure-drop monitoring
- Online crude compatibility indicators

5.6 Quantified Economic Benefits: Online Analyzers on a 100,000 BPD CDU

The following benefit statement, drawn from MODCON Process Intelligence operating data and published industry benchmarks, quantifies the annual value of a combined salt-in-crude and NIR analyzer installation on a representative 100,000 BPD CDU operating 350 days per year:

Benefit Item	Annual Value	Analyzer
SALT-IN-CRUDE ANALYZER		
Wash water reduction (15% saving)	$336,000	SALT
Demulsifier & chemical savings (20%)	$200,000	SALT
Overhead corrosion / equipment life extension	$150,000	SALT
Avoided unplanned shutdowns (probability-weighted)	$200,000	SALT
Opportunity crude access (10,000 BPD @ $0.80/bbl)	$2,800,000	SALT
Sub-total — Salt Analyzer	**$3,686,000**	

NIR ANALYZER + APC		
Kerosene give-away elimination (400 BPD @ $4.00/bbl)	$560,000	NIR
Other cut-point give-away (naphtha, diesel interfaces)	$380,000	NIR
Off-specification production avoidance	$1,000,000	NIR
Furnace energy savings — 4% reduction	$500,000	NIR
Stripping steam reduction — 7%	$280,000	NIR
Carbon cost reduction — 14.2% CO_2 @ $25/tonne	$530,000	NIR
Sub-total — NIR + APC	**$3,250,000**	
COMBINED ANNUAL BENEFIT (100,000 BPD CDU)	**$6,936,000**	

5.7 Capital Cost and Payback

System	Installed Capital	Annual Benefit	Payback
Salt-in-Crude Analyzers (2 units: inlet + outlet)	$280,000–$380,000	$3,686,000	< 5 weeks
NIR Analyzer (1 unit, 5 multiplexed streams)	$450,000–$650,000	$3,250,000	< 9 weeks
Combined program (incl. APC integration)	**$1,200,000–$1,500,000**	**$6,936,000**	**≈ 9 weeks**

The opportunity crude benefit alone — USD 2.8 million per year — repays the entire combined capital program within 14 weeks. At a 10% discount rate over a 7-year equipment life, the net present value of the combined investment exceeds USD 25 million. For context, the capital cost of the analyzer program is equivalent to approximately four days of CDU operating margin for a well-run refinery.

5.8 Recommended Modcon Analyzer Architecture

A recommended Modcon CDU optimization architecture may include the following layers:

1. **Salt-in-Crude Measurement**
   MOD-4100S salt-in-crude analyzers installed at the crude inlet, desalter inlet and/or desalter outlet to monitor crude salt loading and desalter efficiency.
2. **Product Quality Measurement**
   NIR analyzer with multiplexed optical channels for real-time monitoring of naphtha, kerosene, diesel and gas oil product streams.
3. **Total Chlorine Measurement**
   Total Chlorine analyzer to detect both inorganic and organic chlorine sources and support corrosion risk management.
4. **Crude Characterization Layer**
   Online crude quality monitoring for API gravity, density, sulfur, viscosity, TAN, H_2S and water content.
5. **DCS / Historian Connectivity**
   Analyzer data transmitted to the DCS and historian using Modbus, OPC-UA or other refinery-approved communication protocols.

6. **APC Integration**
   Online analyzer data used as feedback and feed-forward variables for desalter control, cut-point optimization, furnace control and product quality management.
7. **Digital Twin / AI Optimization Layer**
   Reconciled process and analyzer data used to calibrate CDU models, predict fouling, support crude switching and generate economic set-point recommendations.

5.9 MODCON-AI CDU Optimisation: Field Results

Published operating data from a live MODCON-AI CDU Optimisation Suite deployment on a 150,000 BPD unit — integrating online salt and NIR analyser data into a continuously calibrated ANN model — demonstrates what is achievable when online analyzers are fully integrated with APC and digital twin technologies:

$12.6M	2.4 months	−2.58%	$1,475
Additional profit / year	Full ROI payback period	Reduction in specific energy intensity	Incremental profit per operating hour

Optimization Insight: The "Give-Away" Problem
CDU operators often over-purify products to ensure specification compliance — for example, keeping diesel flash point 5°C above the minimum specification. APC tightly controls product quality to the specification limit, eliminating this "quality give-away." Recovering even 1% of diesel that was previously over-stripped into naphtha can add hundreds of thousands of dollars per year in a large CDU.

5.10 The Five-Layer Crude Intelligence Strategy

As refineries process increasingly diverse crude slates — including opportunity, heavy, and high-contaminant grades — a single salt-in-crude measurement is no longer sufficient to fully characterize corrosion risk, feed quality, and product performance. Leading refiners are adopting a Five-Layer Crude Intelligence Strategy that provides complete visibility across the CDU operating envelope:

Layer 1 — Salt-in-Crude Measurement (Desalter Optimization)

Continuous electrometric salt measurement (ASTM D3230) at the desalter inlet (S2) and outlet (S3) enables closed-loop control of wash water injection and demulsifier dosing. Monitoring salt removal efficiency in real time — rather than waiting for laboratory shift samples — allows operators to detect desalter upsets within minutes and prevent salt carryover events before they initiate fouling or catalyst poisoning.

Layer 2 — Total Chlorine Measurement (Corrosion Risk Management)

Salt measurement alone does not capture the full corrosion risk. Modern crude streams may contain organic chlorides — chlorinated solvents, chemical treatment residues, and transportation contaminants — that pass through the desalter unchanged and decompose at furnace temperatures to generate HCl. XRF Total Chlorine analyzers measure chlorine from all sources and answer a different question from the desalter salt analyzer: not "how efficiently is the desalter working?" but "how much total HCl precursor is entering the fractionation system?" This information is critical for crude acceptance decisions, blend optimization, and overhead neutralizer dosing.

Layer 3 — Online Crude Characterization (Feed Quality Monitoring)

Corrosion and operational performance depend on more than chlorides alone. Real-time crude characterization — covering API gravity, density, sulfur content, viscosity, Total Acid Number (TAN), H_2S, and water content — provides the APC and LP optimization systems with an accurate, up-to-date picture of the crude entering the CDU. Without this, the APC is responding to crude that may have been characterized by a laboratory assay hours or days earlier. Feed quality uncertainty is the primary driver of unnecessary product quality give-away and off-specification events.

Layer 4 — Corrosion Monitoring (Asset Protection)

Predictive measurements require validation against actual equipment condition. Corrosion monitoring — through electrochemical sensors, ultrasonic thickness measurement, or corrosion coupon analysis — verifies that the levels of HCl and other corrodents predicted from upstream measurements are translating (or, when the system is working correctly, not translating) into actual metal loss. Corrosion rate data also quantifies the effectiveness of chemical inhibitor programmes, enabling dosage optimization rather than conservative fixed-rate injection.

Layer 5 — Product Quality Verification (CDU Performance Optimization)

The ultimate objective of CDU operation is producing on-specification products at maximum margin. Online NIR analyzers on all product draw streams (N1–N5) close the quality feedback loop, enabling APC to control cut points at — rather than safely inside — specification limits. The economic consequence of this tightening is the give-away elimination quantified in the ROI table above: every degree Celsius that the cut point can be held closer to the specification limit converts lower-value product into higher-value product continuously.

Enabling the Digital Stack

The five measurement layers are not independent monitoring systems — they are the data foundation on which APC, digital twins, and AI optimization operate. A digital twin cannot accurately predict overhead corrosion without Total Chlorine data. An APC controller cannot optimize cut points without real-time product quality feedback. A machine-learning fouling model cannot generate reliable cleaning schedule recommendations without continuous crude quality characterization. The physical analyzers are the connection between refinery reality and the digital optimization layer; without them, the digital systems are optimizing a model that may have diverged significantly from the actual process.

6. Crude Blending & Feedstock Optimization

A refinery's profit margin is critically influenced by its ability to process a diverse slate of crude oils, including cheaper "opportunity crudes" (heavy, sour, or high-TAN grades) without sacrificing unit reliability or product quality. CDU optimization therefore extends upstream to the crude selection and blending decision.

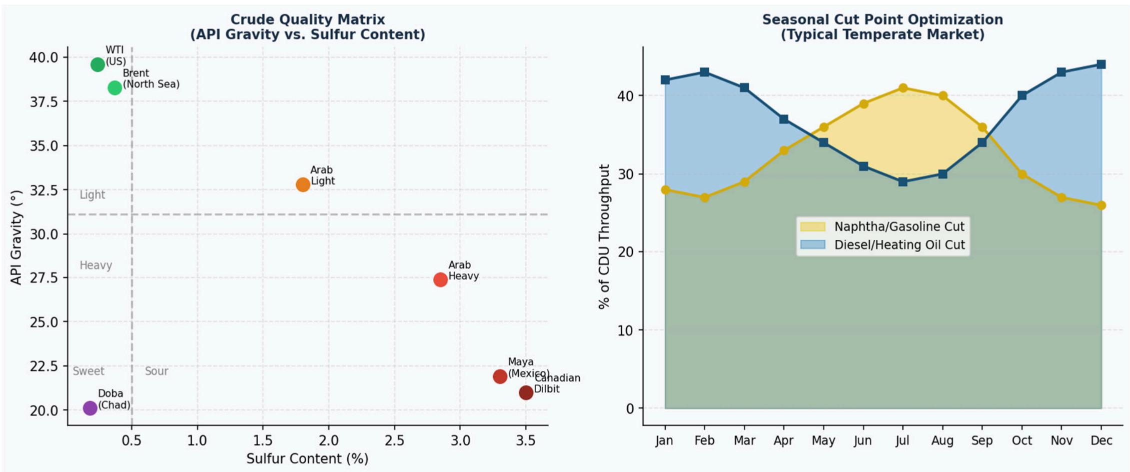

Figure 4 (left): Crude Quality Matrix — API gravity vs. sulfur content for common benchmark crude grades. Light, sweet crudes (upper left quadrant) are easiest to process but command a market premium; heavy, sour crudes (lower right) are discounted but require more intensive processing. (right): Seasonal cut point optimization — refineries shift naphtha/diesel production ratios to track seasonal market demand.

6.1 Crude Characterization & Assay Management

Accurate crude oil assay data — the full distillation curve, density, sulfur, nitrogen, metals (Ni, V), Total Acid Number (TAN), and salt content — is the foundation of blending optimization. Refineries maintain a library of assays for all crudes in their procurement portfolio and use regression-based or artificial neural network (ANN) models to interpolate properties for untested blends.

6.2 Crude Acceptance and Switching Checklist

Before processing a new crude or crude blend, the following checks should be performed:

- Review latest crude assay.
- Confirm API gravity, sulfur, TAN, viscosity and metals.
- Check salt content and expected desalter loading.
- Check BS&W and emulsion stability.
- Evaluate organic chloride / Total Chlorine risk.
- Review compatibility with current crude tank inventory.
- Evaluate asphaltene stability and fouling tendency.
- Confirm furnace duty and tube skin temperature margin.
- Confirm downstream unit feed quality constraints.
- Define temporary APC and operating targets during crude transition.
- Increase monitoring frequency during the crude switch.
- Track desalter outlet salt and product quality in real time.

6.3 Cut-Point Optimization Engineering Notes

Cut-point optimization should not be performed only on the basis of column temperature profiles. Reliable online quality feedback is required to avoid off-specification production or excessive quality give-away.

Key engineering requirements include:

- online distillation or NIR property prediction;
- validated product quality models;
- defined product specification limits;
- clear economic value for moving material between adjacent cuts;
- APC constraints for column pressure, draw rates, pumparound duties and furnace limits;
- operator-approved procedures for seasonal product mode changes.

6.4 Linear Programming Crude Selection

Refinery-wide LP models (e.g., Honeywell RPMS, AspenTech PIMS, or KBC Petro-SIM) optimize crude selection and blending ratios to maximize refinery margin subject to constraints including:

- CDU throughput capacity and hydraulic limits (column flooding, pump suction head).
- Furnace duty and metallurgical limits (maximum tube outlet temperature, sulfidation allowance).
- Desalter capacity and wash water availability.
- Product specification requirements and downstream unit feed quality windows.
- Crude logistics constraints (tankage, pipeline nominations, port scheduling).

6.5 Cut Point Optimization

Within a given crude slate, the CDU operator can shift product yields by adjusting the "cut points" — the temperature boundaries between adjacent fractions. A 2°C shift in the kerosene/diesel cut point can move tens of tonnes per day between the two fractions. Optimization of cut points is performed in real time by the APC application, and over longer horizons by the LP planner, subject to both operational constraints and market price signals.

Seasonality plays a major role: refineries in temperate climates maximize naphtha and gasoline production in summer and shift to diesel and heating oil mode in winter, as illustrated in Figure 4 (right).

7. Digital Technologies & Artificial Intelligence

The convergence of Industrial IoT (IIoT) sensor networks, cloud computing, and machine learning has opened new optimization pathways that were impractical a decade ago. Modern refineries are increasingly deploying digital twin platforms, AI-based soft sensors, and autonomous optimization agents to complement traditional APC systems.

7.1 Digital Twin Data Requirements

A CDU digital twin requires high-quality, time-aligned data from the physical unit. The minimum data requirements include:

- validated process measurements from DCS;
- online analyzer data;
- laboratory reference data;
- crude assay and crude blend information;
- equipment design data;
- heat exchanger network configuration;
- furnace efficiency and combustion data;
- product specifications and economic values;
- operating constraints and alarm limits;
- maintenance and fouling history.

Without reliable online analyzer data, a digital twin may remain mathematically sophisticated but operationally disconnected from the actual refinery process.

7.2 Machine Learning & Data-Driven Models

Where first-principles models are too slow or complex for real-time application, data-driven models built from historical plant data provide a pragmatic alternative. Gradient-boosted tree models and deep neural networks have been successfully applied to:

- Fouling prediction: Forecasting the rate of heat exchanger U-value decline as a function of crude properties, operating temperature, and flow velocity, enabling proactive cleaning scheduling.
- Crude quality inference: Estimating crude TAN, viscosity, and distillation curve properties from low-cost process measurements when laboratory assays are unavailable.

- Furnace tube life prediction: Estimating remaining life of radiant tubes based on cumulative exposure to high temperatures.

A notable published example demonstrated that a neural network with autoregressive exogenous (NARX) model structure, trained on 18 months of CDU operating data, could predict furnace outlet temperature and product yield to within 1% accuracy under unknown feed composition — sufficient for closed-loop optimization.

7.3 Human-in-the-Loop AI Deployment Principle

Emerging AI-based optimization agents (reinforcement learning agents deployed within digital twin environments) are beginning to enter industrial pilots. These agents explore the CDU operating envelope autonomously, learn the non-linear trade-offs between energy, yield, and product quality, and propose operating policies that outperform expert-designed APC set-point profiles. While full autonomy remains aspirational for safety-critical refinery operations, hybrid human-in-the-loop architectures — where the AI proposes and a human approves — are gaining acceptance.

AI-based CDU optimization should initially be deployed as a human-in-the-loop advisory system. The AI model may recommend set-point changes, crude switching strategies, cleaning schedules or operating modes, but final approval should remain with qualified refinery personnel.

Recommended approval workflow:

1. AI identifies optimization opportunity.
2. Process engineer reviews feasibility and constraints.
3. APC engineer confirms controller readiness.
4. Operations team reviews safety and operability.
5. Approved recommendation is implemented through APC or DCS.
6. Actual benefit is measured and compared with predicted benefit.

This approach allows refineries to capture AI value while maintaining safety, accountability and operator confidence.

8. Energy Efficiency & Emissions Reduction

The CDU is the largest single source of direct CO_2 emissions within a refinery, accounting for 20–40% of total site greenhouse gas output depending on configuration. With tightening carbon regulations (EU ETS, IRA clean hydrogen incentives, IMO bunker fuel standards) and internal corporate net-zero commitments, CDU energy optimization has taken on a strategic dimension beyond pure economics.

8.1 Furnace Efficiency Optimization

Combustion optimization is the fastest-payback energy project available to a CDU. Key actions include:

- Excess air minimization: Reducing flue gas O_2 from 4% to 2% typically improves furnace thermal efficiency by 1–2%.
- Air preheat: Recovering heat from flue gases to preheat combustion air is standard on new furnaces and a common retrofit on existing units.
- Automated draft control: Maintaining optimal firebox pressure through automated damper control prevents air infiltration (which dilutes flue gas and wastes heat).
- Infrared tube inspection: Regular IR camera surveys identify developing hot spots and pass flow maldistribution before tube failures occur.

8.2 Pumparound Heat Recovery

Pumparounds — streams of liquid drawn from the fractionator, cooled in heat exchangers against the crude preheat train, and returned to the column — are a powerful mechanism for recovering heat from the column at precisely the temperature level where it is most useful for crude preheating. Optimizing pumparound duties and return temperatures is one of the levers available to the APC application and can significantly shift energy from the furnace (high-temperature, high-cost) to the pumparounds (medium-temperature, recovered energy).

8.3 Retrofits & Capital Projects

For longer-term emissions reduction, refineries are investing in:

- Heat exchanger network expansions: Adding new exchangers identified by pinch analysis to close the gap between current and minimum energy targets.
- Column internals replacement: Replacing older bubble-cap or sieve trays with high-efficiency structured or valve trays to reduce pressure drop and improve separation, allowing lower stripping steam rates.
- Electrification of reboilers and heaters: Replacing fired heaters with electric heat pumps or resistance heaters in scenarios where low-carbon electricity is available.
- Hydrogen co-firing: Blending low-carbon hydrogen into furnace fuel gas as an intermediate step toward decarbonization.

8.4 Energy and Emissions Calculation Methods

Energy and emissions benefits should be quantified using transparent assumptions.

Recommended calculation inputs:

- CDU feed rate
- operating days per year
- furnace fuel gas price
- fuel gas heating value
- furnace efficiency
- reduction in furnace duty
- steam reduction
- electricity cost
- CO_2 emission factor
- carbon price or internal carbon cost

Recommended outputs:

- annual fuel saving;
- annual steam saving;
- annual CO_2 reduction;
- annual carbon cost saving;
- payback period;
- net present value where applicable.

This calculation should be included in every CDU optimization project justification.

9. Case Study: Preheat Train Crash & Recovery

The following case study illustrates how a seemingly routine crude switch can cascade into a major CDU performance event — and how integrated optimization tools enabled rapid diagnosis and recovery.

Parameter	Detail
Location	Mid-Continent Refinery, USA
Unit Capacity	120,000 BPD Atmospheric CDU
Equipment Affected	E-101 A–D (Crude/Residue Interchangers, Preheat Train)
Root Cause	Desalter upset on crude switch to high-BS&W heavy crude
Impact	FIT dropped from 220°C to 180°C; throughput cut 20,000 BPD

Parameter	Detail
Recovery Time	48 hours (online chemical cleaning, no unit shutdown)

Table 3: Case Study Summary — Preheat Train Crash at a 120,000 BPD CDU

9.1 Incident Sequence

The refinery switched from a light sweet crude (API 38°, sulfur 0.4%) to a cheaper heavy sour opportunity crude (API 24°, sulfur 2.8%, BS&W 0.6%) without adjusting the desalter wash water rate or demulsifier dosage. The high basic sediment and water (BS&W) content of the new crude overwhelmed the desalter's separation capacity.

Brine slippage into the preheat train caused water flash at temperatures above 150°C, depositing solid salt crystals that acted as nucleation sites for asphaltene precipitation. Within 36 hours, the overall heat transfer coefficient (U-value) of exchangers E-101 A–D had fallen by 45%, reducing the furnace inlet temperature from 220°C to 180°C. The fired furnace reached maximum duty at 25% excess firing, and the CDU was forced to reduce throughput by 20,000 BPD to maintain the required transfer temperature of 350°C.

9.2 Diagnosis & Response

Real-time monitoring of U-values in the digital twin platform flagged the performance degradation within 8 hours of the crude switch — far earlier than it became visible to operators through temperature measurements alone. The engineering team deployed an online chemical cleaning strategy:

- Injection of a terpene-based dispersant solvent into the crude stream upstream of the fouled exchangers.
- Staged flow surging to mechanically dislodge softened foulant deposits.
- Continuous monitoring of U-values and pressure differentials to track cleaning progress.

Within 48 hours, U-values recovered to 85% of clean design, the FIT rose by 35°C to 215°C, and the unit returned to full throughput. The online approach avoided a planned shutdown that would have cost an estimated USD 4–6 million in lost margin.

9.3 Case Study Engineering Lessons

The case study demonstrates that crude switching risk should be managed proactively rather than reactively.

Key engineering lessons:

- Crude switches require pre-defined operating procedures.
- Desalter settings must be adjusted before the new crude reaches the unit.
- Online salt measurement at the desalter outlet provides early warning of salt carryover.
- Fouling detection through U-value monitoring is faster than waiting for visible FIT loss.
- Laboratory analysis alone is too slow for fast crude transitions.
- Online analyzers should be connected to APC or operator advisory systems.
- The economic impact of one fouling event may exceed the installed cost of online measurement.

This incident reinforced several best practices now embedded in the refinery's operating procedures:

- Crude compatibility screening (asphaltene stability ratio, desalter treatability tests) must be completed before any crude switch.
- Desalter operating parameters (wash water rate, interface level, electrostatic field voltage) must be adjusted proactively when switching to crudes with higher BS&W or higher emulsion stability.
- U-value monitoring thresholds in the digital twin must trigger automatic alerts when fouling rates exceed the baseline model prediction by more than 15%.

Online salt-in-crude analyzers at the desalter outlet (S3) would have detected salt carryover within minutes of the crude switch — well before fouling reached a detectable level in heat exchanger temperatures. Had this data been available to the APC system, automatic feed-forward correction to wash water rate and demulsifier dosing could have maintained desalter efficiency through the transition. The USD 1.2 million cost of this event (emergency chemical treatment and production deferral) compares unfavourably to the USD 280,000–380,000 installed cost of a two-point salt analyzer installation.

10. Challenges & Risk Factors

CDU optimization does not occur in isolation. Several factors can limit the realization of theoretical benefits, and a thorough optimization program must account for these risks.

10.1 Crude Variability & Uncertainty

Crude oil properties vary both between different crude grades and within the same grade depending on the source reservoir's production stage and any upstream treatment. APC controllers and optimization models are only as good as their crude quality inputs. Uncertainty in feed composition is the primary driver of product quality upsets, which is why investment in online crude property analyzers (NIR, NMR) and improved crude assay management directly underpins optimization performance.

A further dimension of crude variability that is often underweighted in CDU optimization programmes is the presence of organic chlorides. Unlike inorganic salts — which are largely removed by the desalter — organic chloride compounds (chlorinated solvents, chemical treatment residues, pipeline contamination) pass through the desalter and decompose at furnace temperatures to generate HCl. Their concentration in the crude stream is highly variable and not correlated with the inorganic salt content. Total Chlorine measurement (Layer 2 of the Five-Layer Crude Intelligence Strategy, Section 5.5) addresses this gap and should be considered a prerequisite for any refinery processing variable or opportunity crude slates.

10.2 Equipment Constraints & Reliability

Throughput and yield optimization is constrained by the hydraulic capacity of trays (flooding), furnace duty limits, pump capacities, and metallurgical limits of piping and vessels processing high-sulfur and high-TAN crudes. Optimization models must encode all hard constraints to prevent solutions that violate equipment integrity limits. Running close to constraints also amplifies the consequence of any equipment failure, so optimization must be balanced against operational resilience.

10.3 Model Maintenance

APC applications degrade over time as the process changes (new equipment, catalyst changes, crude slate shifts) and model parameters drift. Industry data suggests that without active maintenance, APC performance degrades by 20–40% within 2–3 years of initial commissioning. Continuous model updating — both through scheduled re-identification campaigns and through adaptive online parameter estimation — is essential to sustain value.

10.4 Organizational & Cultural Factors

Optimization tools create value only when operators and engineers trust and use them. Resistance to APC (operators placing controllers in manual to maintain perceived control), poor data quality (manual workarounds, bypassed instruments), and lack of cross-disciplinary collaboration (process engineers isolated from IT/data science teams) are the most commonly cited barriers to realizing optimization potential. Organizational change management, operator training, and cross-functional optimization teams are as important as the technical solutions themselves.

10.5 Common CDU Optimization Mistakes

Common mistakes that reduce CDU optimization value include:

- Optimizing cut points without reliable online product quality measurement.
- Relying only on laboratory data during fast crude transitions.
- Treating salt-in-crude measurement as a substitute for Total Chlorine measurement.
- Installing analyzers without validating sample conditioning and response time.
- Running APC without active model maintenance.
- Ignoring exchanger fouling until furnace inlet temperature loss becomes severe.
- Optimizing throughput without respecting furnace, metallurgy and column hydraulic constraints.
- Building a digital twin before resolving data quality and analyzer availability problems.
- Evaluating ROI only on energy savings while ignoring yield, off-spec, corrosion and crude flexibility benefits.
- Failing to train operators and engineers on how optimization recommendations should be used.

10.6 Engineering Risk Review Checklist

Before implementing CDU optimization changes, the following risks should be reviewed:

- furnace tube skin temperature and coking risk;
- column flooding or weeping risk;
- exchanger pressure drop and hydraulic limitations;
- corrosion risk in overhead system;
- desalter stability and brine carryover;
- product off-specification risk;
- downstream unit feed quality constraints;
- analyzer reliability and sample system plugging risk;
- APC controller constraint configuration;
- cybersecurity and data integrity for digital systems;
- operator readiness and management of change requirements.

11. Conclusion & Recommendations

The Crude Distillation Unit remains the most leveraged optimization target in any petroleum refinery. Improvements in CDU performance cascade through every downstream unit and directly determine the refinery's energy intensity, emissions profile, product yield, and operating margin. The convergence of advanced process control, rigorous process simulation, digital twins, and artificial intelligence has dramatically expanded what is achievable — and has reduced the investment required to capture value.

The following prioritized roadmap summarizes the recommended sequence of optimization initiatives for a CDU seeking step-change performance improvement:

#	Initiative	Timeline	Typical ROI
1	Desalter performance audit & wash water optimization	1–3 months	< 6 months payback
2	Preheat train U-value monitoring & cleaning schedule optimization	3–6 months	6–18 months
3	Online NIR analyzers for product quality feedback	6–12 months	12–24 months
4	APC (MPC) implementation / reactivation & model refresh	9–18 months	12–30 months
5	Crude blending optimization integrated with LP planner	12–24 months	18–36 months
6	Digital twin deployment & AI-based soft sensors	18–36 months	24–48 months
7	HEN retrofit / capital project (pinch analysis basis)	2–4 years	2–4 year payback

Table 4: CDU Optimization Roadmap — recommended sequence of initiatives with indicative timelines and payback periods.

Ultimately, CDU optimization is not a project with a completion date — it is an ongoing operational discipline. The refineries that achieve the greatest sustained performance are those that embed optimization thinking into every layer of the organization: from the operators adjusting set points on the DCS to the engineers interrogating the digital twin, to the commercial team selecting next month's crude slate. In an industry facing simultaneous pressures from the energy transition, tightening environmental regulation, and feedstock diversification, CDU optimization has never been more important — or more technically rich — than it is today.

The measurement foundation matters as much as the algorithms that build on it. Online analyzers — salt-in-crude instruments, NIR spectrometers, Total Chlorine meters, and online crude characterization systems — are not peripheral instrumentation. They are the sensory system of the optimized CDU: without them, the APC is flying blind, the digital twin is running on stale data, and the LP optimizer is selecting crudes based on assays that may be weeks old. The Five-Layer Crude Intelligence Strategy described in Section 5.5 provides a structured framework for building this measurement foundation systematically, with each layer delivering standalone value while also enabling the layers above it.

The economics are clear. For a 100,000 BPD CDU, the combined annual value of online salt and NIR analyzers alone exceeds USD 7 million against a capital investment of USD 1.2–1.5 million — a payback measured in weeks. When integrated with a digital twin and AI optimization layer (as demonstrated by MODCON-AI field results on a 150,000 BPD unit achieving USD 12.6 million in incremental annual profit), the combined return on the full measurement-to-margin investment stack represents one of the highest-ROI capital allocations available in refinery operations today.

11.1 Practical Implementation Roadmap

A practical CDU optimization program should be implemented in phases.

Phase 1 — Baseline Assessment

- Review historical CDU operation.
- Identify energy, yield, quality and reliability gaps.
- Evaluate analyzer coverage and data quality.
- Review APC availability and service factor.
- Estimate current product give-away and energy penalty.

Phase 2 — Measurement Foundation

- Install or validate salt-in-crude analyzers.
- Install or validate NIR product quality analyzers.
- Add Total Chlorine measurement where organic chloride risk exists.
- Connect analyzer data to DCS, historian and APC.
- Validate analyzer response time and calibration.

Phase 3 — APC and Control Improvement

- Refresh MPC models.
- Add analyzer feedback to APC.
- Implement cut-point optimization.
- Improve furnace and pumparound control.
- Track APC service factor and economic benefit.

Phase 4 — Digital Twin and AI Integration

- Build reconciled CDU model.
- Integrate crude assay and online analyzer data.

- Add fouling prediction.
- Add crude switching advisory.
- Deploy AI-based economic set-point recommendations.

Phase 5 — Continuous Improvement

- Review KPIs monthly.
- Validate models quarterly.
- Audit annual benefits.
- Update crude assay and analyzer models.
- Link turnaround planning to long-term optimization opportunities.

11.2 Roles and Responsibilities

Successful CDU optimization requires clear ownership across multiple disciplines.

Function	Responsibility
Process Engineering	Define operating envelope, constraints and economic benefit calculations
Operations	Execute approved set-point changes and maintain APC in service
Analyzer Team	Ensure analyzer availability, calibration and validation
APC Engineer	Maintain MPC models and controller performance
Reliability / Inspection	Monitor fouling, corrosion and equipment integrity limits
Planning / Scheduling	Align crude selection and LP optimization with CDU capabilities
Digital / Data Team	Maintain historian, dashboards, digital twin and AI models
Management	Approve budget, prioritize projects and review KPI performance

12 References & Further Reading

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- ASTM D86 — Distillation of Petroleum Products
- ASTM D93 — Flash Point by Pensky-Martens Closed Cup Tester
- ASTM D4737 — Calculated Cetane Index
- Relevant IEC / ATEX / hazardous area standards for online analyzer systems
- Refinery corrosion control guidelines for chloride management
- Site-specific APC, DCS and cybersecurity standards
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