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IMP INTELLIGENCE SERIES

Catalyst Liability

Protecting the Balance Sheet from Process Failures

What Contracts, Risk-Sharing Models, and Emerging Technologies Mean for Refining and Petrochemical Operators

KEY FIGURES

$27.2B Global catalyst market 2024 *Source: Grand View Research*	**$8.27B** Global refinery catalyst market 2024 *Source: Polaris Market Research*	**74%** Top 4 FCC catalyst suppliers' market share *Source: Intel Market Research*	**£1.325B** Honeywell · Johnson Matthey Catalyst Tech deal *Source: Honeywell / Benzinga (Feb 2026)*
~$6M/yr FCC catalyst spend, 30,000 bpd unit *Source: Becht Engineering*	**$1.2–3M** Lost production per day of turnaround delay *Source: U.S. EIA / Valero filings*	**>95%** China platinum group metal import dependency *Source: World Platinum Investment Council*	**+15%** Catalyst life extension from ML platforms *Source: Mordor Intelligence (2026)*

Catalyst Bed Damage · Process Chemicals · Silicon Poisoning · FCC · Hydroprocessing · Hydrocracking · Catalyst Deactivation · Limited Warranty · Liability Caps · Risk-Sharing · PGM Leasing · Performance Guarantees · BASF · Grace · Albemarle · Sinopec · Honeywell UOP · Topsoe · Clariant · Axens · Evonik · Johnson Matthey · AI in Catalysis · Open Catalyst Project · MLIPs · Single-Atom Catalysts · Biocatalysis · MOFs · Green Hydrogen · SAF · e-Methanol · IMO 2020 · Tier 3 · Critical Minerals · South Africa PGMs · DRC Cobalt · Indonesia Nickel · Turnaround Risk

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2026

1 Executive Summary

The catalyst is the most concentrated single point of value — and risk — in a refining or petrochemical asset. A modern fluid catalytic cracking (FCC) unit consumes catalyst at four to five tonnes per day; for a 30,000 bpd unit that is a recurring spend in the order of USD 6 million per year before any incident. A hydrocracker or pretreater bed represents a single-asset capital exposure that can run from low single-digit millions for a small unit to USD 5 million or more for a major reactor charge. Beyond that sits the second-order loss: the U.S. EIA documents that a 29-day FCC turnaround at Valero's St. Charles refinery cost USD 39 million, with delay penalties of USD 1.2 to 3 million for each additional day. The American Petroleum Institute reports that major turnarounds can run to USD 200 million or more, and unplanned outages caused by catalyst failure compress all of those costs into a single, unbudgeted event.

Despite this exposure, the contractual architecture between catalyst suppliers and plant operators is heavily asymmetric. Standard catalyst supply agreements place the financial risk of process-chemical contamination almost entirely on the operator. Typical clauses limit the supplier's liability to replacement of the defective product, exclude all consequential and indirect damages, cap aggregate liability at one year of payments, and include broad customer-assumption-of-risk language for any process outcome. The reality in court and arbitration is consistent: when a process chemical — an antifoam containing polydimethylsiloxane, a corrosion inhibitor, a recycled solvent — destroys a catalyst bed, the question of who pays is decided less by the catalyst supply contract than by the operator's insurance, the process chemical supplier's own warranty position, and the evidentiary chain proving who introduced what.

This paper has three goals. First, to map the actual cost geometry of catalyst failure — what is destroyed, what is foregone, and what gets paid by whom under typical contract structures. Second, to survey the risk-sharing models that are quietly displacing outright purchase: precious metal leasing, consigned inventory, performance guarantees tied to feedstock specifications, and regeneration contracts that can recover 40 to 60 percent of fresh-catalyst value. Third, to widen the lens — to assess catalyst market structure, the supply chain of the metals that make modern catalysts work, the AI tools that are now in commercial deployment, and the next-generation chemistry (single-atom catalysts, MOF-derived electrocatalysts, biocatalysis, bio-silicone) that will reshape the competitive landscape over the next decade.

Contract Reality	Risk Architecture	Strategic Shift
Standard catalyst supply agreements: replacement-only remedy, no consequentials, 1-yr liability cap. The contract does not absorb the operator's loss; insurance and process-chemical supplier warranties do — if the evidentiary chain holds.	Process chemicals (antifoams, corrosion inhibitors, anti-fouling additives, cleaning solvents) are the most under-monitored cause of catalyst poisoning. Silicon, sulfur, sodium, phosphorus, and arsenic at ppb levels can permanently deactivate downstream beds.	Leasing PGMs, consigned inventories, performance guarantees, regeneration contracts and digital monitoring are migrating operators away from the buy-and-pray model. The Honeywell–Johnson Matthey deal accelerates this consolidation.

NOTE ON SCOPE, SOURCES, AND LIMITATIONS

This is a strategic intelligence brief for industrial operators, procurement leads, and technical buyers in refining, petrochemicals, and adjacent process industries. It is not an original scientific contribution and does not present new experimental data. The purpose is to synthesise public-domain information — peer-reviewed literature where available, primary regulatory and trade-association data, company disclosures, and third-party market research — into a usable picture of catalyst-related liability, risk architecture, and adjacent industry dynamics. Source categories are mixed by design and differ in evidentiary weight; readers should weight them accordingly.

Caveats the reader should carry through the document: (i) **Market size estimates vary materially across analysts.** Public estimates of the global catalyst market for 2024 range from approximately USD 21.6 billion (industrial catalysts subsegment, Precedence Research) to USD 43.0 billion (broad definition, Maximize Market Research) — see Section 2.1 for the detailed analyst comparison. We use the most commonly cited mid-range figure (USD 27 billion, Grand View Research / MarkNtel) as the working anchor and disclose the range. (ii) **Public quantified data on catalyst-poisoning incident frequencies is rare.** Insurance loss data is not disclosed at industry level; operator disclosure is selective. Cited cases (Marathon CCR silicon breakthrough; the 2007 UK gasoline silicon incident; Tosco Avon 1997) are illustrative, not statistical samples. Operator-survey aggregates (AFPM Q&A series) are the closest substitute and are referenced where applicable. (iii) **Specific market-share figures (e.g., the >74% top-four FCC catalyst share) come from third-party market research** rather than independently verifiable disclosures. These are cited with the source named so the reader can apply their own confidence weight. (iv) **Performance figures from individual vendors** — including the 15% catalyst service-life extension associated with Topsoe and Honeywell ML platforms — reflect vendor-reported or industry-analyst aggregated outcomes and have not been independently audited in this paper. (v) **IMP perspective.** IMP InterMediaPartners is a B2B market intelligence and communications consultancy; clients in this domain include specialty chemical and petrochemical producers. Readers should weigh that disclosure when interpreting directional commentary in Sections 4–10.

2 The Catalyst Bandwidth: Where, Why, and How Much

Catalysts are the chemistry that makes modern industrial production economically possible. They lower activation energy, raise selectivity, and convert one molecule into another at rates and yields no thermal or stoichiometric process can match. Without them, no current refinery would meet sulfur regulations, no ammonia plant would meet feedstock costs, and no automotive exhaust system would meet emission standards. They are also a value concentration: a few kilograms of formulated zeolite or supported metal can determine the throughput economics of an entire processing unit.

2.1 The Global Catalyst Market — and Why the Headline Number Varies

Headline market-size figures for the global catalyst market vary materially across analysts because the segment definition itself varies. Some sources include automotive emission-control catalysts in the headline; others report them separately. Some include refining and petrochemicals only; others extend to fine chemicals and biocatalysts. The table below collects the public estimates we have been able to verify and shows the range. Three observations follow: the absolute size estimates span roughly USD 21 billion to USD 43 billion for 2024 depending on segment scope; the growth rate is much more consistent across sources at approximately 4 to 5 percent CAGR; and Asia-Pacific is uniformly the dominant region at 35 to 39 percent of revenue. We use the Grand View / MarkNtel mid-range figure (USD 27.2 billion, 2024) as the working anchor in this paper because it is the most frequently cited in industry reporting, but the reader should carry the wider range when interpreting growth implications.

Source	Scope	2024 size (USD)	Forecast	CAGR
Grand View Research / MarkNtel	Catalyst market, broad	27.18 B	33.19 B by 2030	~4.1%
Zion Market Research	Catalyst market	32.16 B (2023)	49.12 B by 2032	~4.8%
NextMSC	Catalyst market	37.70 B	49.04 B by 2030	~4.5%
Precedence Research	Catalyst market, broad incl. emission control	40.38 B	65.78 B by 2034	~5.0%
Precedence Research	Chemical catalysts (narrower)	41.29 B	64.04 B by 2034	~4.5%
Maximize Market Research	Catalyst market	42.98 B	63.02 B by 2032	~4.9%
Precedence Research	Industrial catalysts subsegment	21.56 B	34.52 B by 2034	~4.8%
Precedence Research	Precious metal catalysts only	55.17 B	143.2 B by 2034	~10.0%

Sources: Grand View Research (2025); MarkNtel Advisors (2025); Zion Market Research (Dec 2024); NextMSC (Dec 2025); Precedence Research catalyst, chemical-catalyst, industrial-catalyst, and precious-metal-catalyst reports (Jan–Jul 2025); Maximize Market Research (Feb 2025). Market sizing varies because analyst segment definitions vary; CAGR is markedly more consistent than absolute size.

Sub-segment estimates (refinery, FCC, hydroprocessing, emission control, biocatalysts) are more consistent across sources than the global headline because the sub-segment boundaries are less ambiguous. The table below uses the most frequently cited figures from refining-specialist analysts and is internally consistent with the analyst comparison above.

Segment	2024–25 size	CAGR	Notes
Refinery catalysts	USD 8.27–9.9 B (2024–25)	~4.0–4.6%	FCC ~38–43% of segment. Hydrotreating fastest sub-segment (5.5%).
FCC catalysts	USD 15.2 B (2024, broader def.)	~4–5%	Top 4 (Grace, BASF, Albemarle, Sinopec) reportedly hold >74% market share per Intel Market Research (2025); IMP has not independently verified.
Hydroprocessing catalysts	USD 2.23 B (2025) → 2.86 B (2035)	~2.5%	Driven by IMO 2020, ULSD, Tier 3 and Euro VI sulfur limits.
Emission-control catalysts	USD 14.0 B (2024) → 31.7 B (2034)	~8.5%	Highest growth driver in the catalyst stack overall — automotive, stationary, marine. PGM-intensive.
Biocatalysts (industrial)	Specialty / specialty-chem niche	>10% in pharma	Mature in pharma APIs and detergents; expanding into bulk and specialty chemicals.

Sources: Grand View Research (2025); Polaris Market Research (2024); Future Market Insights (Feb 2025); Intel Market Research (Dec 2025); Mordor Intelligence (2026); Market Research Future (Nov 2025).

2.2 Where Catalysts Are Used: The Application Bandwidth

The catalyst footprint stretches from very high volume, low margin commodity processes to very low volume, very high margin specialty applications. The economic logic is different at each end of the bandwidth, and so is the contractual exposure when something goes wrong.

Domain	Process / Use	Catalyst Class	Risk Profile
Petroleum refining	FCC, hydrotreating, hydrocracking, catalytic reforming, alkylation, isomerisation, naphtha hydrotreating	Zeolites (USY, ZSM-5), CoMo / NiMo / NiW supported on alumina, Pt/Re on alumina (reforming), Pt/Pd on zeolite (hydrocracking)	Highest direct catalyst-bed exposure to feedstock contaminants. Silicon, arsenic, sodium, nickel, vanadium poisoning all documented at ppb–ppm levels.
Petrochemicals	Steam cracking, propane dehydrogenation (CATOFIN, Oleflex), ethylene oxide, polyethylene / polypropylene, BTX, MTBE	Cr-alumina, Pt-Sn, Ag/alpha-alumina (EO), Ziegler-Natta and metallocene polymerisation, Friedel-Crafts	High-purity feedstock specifications standard. Single oxygen excursion can deactivate Ziegler-Natta beds. Chloride upsets in Pt-Sn dehydrogenation.
Ammonia / fertiliser	Steam reforming, water-gas shift, methanation, Haber-Bosch synthesis	Ni on alumina, Fe-Cr / Cu-Zn-Al, promoted iron	Sulfur is a permanent poison at sub-ppm levels. Pre-reformer guard beds standard.
Methanol / syngas / e-fuels	Methanol synthesis, Fischer-Tropsch, methanol-to-jet, e-methanol, e-SAF (Power-to-Liquid)	Cu-ZnO-Al_2O_3 (methanol), Co or Fe on support (FT), zeolite + metal cascade (MtJ)	Green-hydrogen feed purity sets the catalyst spec. New generation: Topsoe MK-417 SUSTAIN for biogenic-CO_2 methanol.
Pharma / fine chemicals (CDMO)	Hydrogenation, asymmetric synthesis, oxidation, biocatalytic API steps	Pd/C, Pt/C, Rh and Ru complexes, immobilised enzymes (lipases, transaminases, imine reductases)	Quality-by-design and GMP frame the risk. Single batch loss can be six- or seven-figure value if it is a late-stage API step.
Automotive / stationary emissions	Three-way catalysts, diesel oxidation catalysts, SCR, particulate filters, ammonia slip catalysts	Pt, Pd, Rh on cordierite or SiC monoliths; Cu-zeolite and Fe-zeolite for SCR	Sulfur and lead are permanent poisons. The single largest PGM consumer globally — and therefore the largest exposure to PGM price swings.
Energy / hydrogen	Water electrolysis (PEM, alkaline, SOEC), fuel cells, ammonia cracking, carbon-dioxide reduction	IrO_2 (PEM-OER), Pt/C (HER), Ni-Fe oxides (alkaline), single-atom catalysts (emerging), MOF-derived electrocatalysts	PGM dependence is the strategic constraint. Earth-abundant alternatives are the open R&D; frontier with EU and US public funding behind it.

Sources: Topsoe processes pages (2026); BASF and Albemarle product portfolios; Honeywell UOP catalyst literature; Bayer et al. (2025) Angewandte Chemie review on industrial biocatalysis; Sustainable Energy & Fuels (2025) review of MtJ pathway; IEA Global Critical Minerals Outlook 2025.

3 The Cost of Failure: What a Damaged Catalyst Bed Actually Costs

When a catalyst bed is impaired, the loss is rarely the catalyst alone. It is a stack of linked costs — the bed itself, the unplanned outage, the throughput loss, the downstream yield change, the regeneration or replacement logistics, and the long-term effect on the turnaround calendar. Operators who think of catalyst poisoning as a procurement problem consistently underestimate the magnitude of the second- and third-order costs.

3.1 The Cost Stack

Cost Layer	Typical Range (refinery FCC / hydroprocessing)	Driver / Notes
Catalyst replacement (bed)	USD 1–5 M for a single hydroprocessing reactor charge; FCC inventory ~USD 6 M/yr at steady-state for 30,000 bpd.	Direct material cost. Hydrocracking and CCR reformer charges are the highest single-asset exposures.
Forced outage (CAPEX hit)	Documented case: Valero St. Charles 29-day FCC turnaround at USD 39 M; major turnarounds reach USD 200 M+ (API).	Outside contractor mobilisation, scaffolding, isolation, hot work, inspection, vessel entry, catalyst handling.
Lost production (gross margin)	USD 1.2–3 M per day of delay (Valero St. Charles disclosure); larger refineries report USD 1 M+/day routinely.	Crack spreads applied to displaced barrels. Sensitive to product mix, market conditions, alternative supply contracts.
Yield degradation (operating)	Becht: a less active FCC catalyst can cost USD 1.26–2.0 M/year in lost incremental volume swell at USD 60/bbl crude, before product mix adjustments.	Often invisible until benchmarked. The cost-cutting catalyst that destroys selectivity is rarely the cheapest in lifetime cost.
Cascade poisoning	Silicon breakthrough in NHT can deposit on platinum sites in CCR — Marathon documented this at multiple CCR units in the early 2000s.	A single upstream bed failure can take a downstream Pt-reformer offline. PGM loading on a CCR unit alone can be 8,000+ troy oz at current prices.
Insurance excess + premium	Variable; depends on policy structure and incident classification (mechanical, process, product liability).	Insurers increasingly demand documented HSE management, antifoam tracking, and feedstock-specification compliance before paying.
Reputational / commercial	Off-spec product on long-term offtake contract; penalty clauses; potential customer switch.	Rare but material — particularly in specialty petrochemicals where customer qualifications are slow to recover.

Sources: U.S. EIA Refinery Outages report; American Petroleum Institute; Becht Engineering blog (Jul 2025); Marathon CCR experience (AFPM Q&A; 26 and 37); IMP estimate synthesis.

3.2 The Process-Chemical Trigger: How Beds Actually Get Killed

The mechanisms of catalyst deactivation are well-characterised in the peer-reviewed literature. The standard reference — Argyle and Bartholomew's 2015 review in *Catalysts* (vol. 5, pp. 145–269; over 1,500 citations) — classifies deactivation by type (chemical, thermal, mechanical) and by mechanism (poisoning, fouling, thermal degradation, vapour formation, vapour-solid and solid-solid reactions, attrition / crushing). The textbook reference for industrial catalyst deactivation across processes is Bartholomew and Farrauto, *Fundamentals of Industrial Catalytic Processes* (Wiley, 2nd ed., 2006). What follows synthesises this published mechanistic literature with operator-disclosed experience from the AFPM Q&A series and supplier technical documentation.

Catalyst suppliers publish detailed contaminant tolerance specifications. Topsoe's hydroprocessing technical literature lists nickel, vanadium, iron, silicon, arsenic, phosphorus and sodium as primary feedstock poisons effective at ppb–ppm levels. The American Fuel & Petrochemical Manufacturers Q&A series catalogues operator experience: silicon from antifoam at the coker, nitrogen slip from a degraded pretreater, sodium from carryover, sulfur upsets in nickel-based reforming. Marathon's published account of two CCR units experiencing simultaneous silicon breakthrough in the early 2000s remains a teaching case: the cause was traced to silicon entering through an upstream naphtha hydrotreater whose silicon-trapping capacity was exhausted earlier than the model had predicted.

A note on incident-frequency data. Public quantified data on catalyst-poisoning incident rates is rare. Insurers do not publish industry-aggregated catalyst-loss data; operators disclose selectively and typically only when required by regulatory or litigation processes. The case studies cited here (Marathon CCR silicon breakthrough; the 2007 UK gasoline silicon contamination incident from recycled toluene used in semiconductor manufacturing; Tosco Avon hydrocracker runaway in 1997) are illustrative of well-documented modes, not statistical samples of frequency. The AFPM Q&A operator-survey aggregates are the closest substitute and are referenced where applicable. Readers seeking quantified incident frequencies will not find them in the public domain at meaningful resolution; the table below characterises mechanisms and reversibility, not probability.

Poison	Typical Source	Affected Catalyst	Reversibility
Silicon (Si)	Polydimethylsiloxane antifoam (coker, drilling fluids, upstream flow improvers, octane-blending solvent contamination)	NiMo / CoMo hydrotreating (alumina-bound), Pt-reformer downstream	Permanent. Adsorbs to alumina hydroxyl groups; chemically bonded.
Sulfur (S)	Crude variation, recycled streams, mercaptan slip from upstream sweeteners	Ni-based reforming, methanation, Cu-Zn-Al methanol	Permanent at ppm levels for Ni and Cu catalysts; reversible on some noble metals.
Arsenic (As)	Heavy / opportunity crudes, recycled solvents from electronics manufacturing (historical precedent: 2007 UK gasoline silicon incident)	Hydrotreating, reforming	Permanent. Adsorbs irreversibly to active metal sites.
Sodium / alkali (Na, K)	Carry-over from desalter, brackish-water boiler tubes, additive carryover	FCC, hydrocracking, reforming	Permanent. Neutralises acidic active sites in zeolites.
Nickel / vanadium (Ni, V)	Heavy crude / residue feeds; especially Venezuelan, Mexican, Canadian heavy	FCC catalysts (deposited on equilibrium catalyst)	Effectively permanent for the deposited equilibrium catalyst. Managed via catalyst makeup rate.
Nitrogen compounds	Cracked feeds (LCO), shale crudes	FCC acid sites; second-stage hydrocracking catalysts (~14 wppm tolerance documented for some units)	Reversible — but the reversibility window is short and the safety consequences of overshoot are not. Tosco Avon hydrocracker runaway, 1997, illustrates the failure mode.
Coke / fouling	Reactant condensation, polymerisation; aggravated by feedstock olefin and oxygenate content	All hydrocarbon-processing catalysts	Reversible via regeneration. Repeated regeneration shortens catalyst life.

Sources: Topsoe Catalyst Poison Removal page; AFPM Q&A; 23, 26, 37 (silicon and silicon breakthrough); Hydrocarbon Engineering 'Defend against silicon poisoning' (2017); Wikipedia / ScienceDirect catalyst deactivation literature; ICheme Loss Prevention Bulletin 291 (Tosco Avon).

4 The Liability Architecture: Contracts, Warranties, and 'Poison Pills'

The contractual position of a catalyst supplier in a typical industrial agreement is narrower than buyers expect. Standard commercial practice — visible in publicly filed supply agreements and in the boilerplate of major industrial catalyst suppliers — is to warrant the catalyst as conforming to specification at the point of delivery, to limit the remedy for breach to replacement of the non-conforming product, and to exclude consequential, indirect, and incidental damages. The aggregate liability cap is commonly set at the value of payments made under the contract in the 12 months preceding the claim. The customer, in nearly all such agreements, expressly assumes the risk for the results obtained by use of the catalyst in any process, regardless of advice or guidance received from the supplier.

4.1 The Standard Catalyst Supply Contract: Typical Clauses

Clause type	Typical Wording (paraphrased)	Practical Effect
Limited warranty	Catalyst will conform to supplier's published specification at delivery; remedy is replacement of non-conforming material.	Supplier liable only for the cost of the catalyst itself — not for the bed loss, the outage, or the lost production.
No consequentials	In no event will either party be liable for consequential, indirect, incidental, special, exemplary or punitive damages, lost profits or revenues, or diminution in value.	Eliminates the operator's most significant heads of loss: lost throughput, lost margin, lost contracts, reputational harm.
Aggregate cap	Each party's aggregate liability shall not exceed amounts paid (or accrued) under the contract in the 12-month period preceding the event.	Caps total exposure at one annual contract value. For a USD 5 M bed, the supplier's maximum exposure is USD 5 M minus exclusions.
Customer assumption of risk	Customer assumes all risk and liability for results obtained by use of the goods, regardless of any advice or technical guidance from the supplier.	This is the operative 'poison pill' clause: even if the supplier recommended use in a particular configuration, that recommendation does not transfer risk.
Disclaimer of implied warranties	Supplier disclaims implied warranties of merchantability and fitness for a particular purpose.	Removes the legal floor of usability. Buyers must contract for specific performance terms — they are not implied.
Force majeure	Standard force majeure language including raw material disruptions and regulatory action.	Becomes increasingly relevant as silicon metal, cobalt, and PGM supply lines concentrate geopolitically.

Sources: Standard catalyst supply contract templates (SEC EDGAR publicly filed exhibits from listed companies); FW Murphy EICS catalyst warranty (2025); IMP analysis of industry boilerplate. Specific contract terms vary by supplier and customer; the public sample of catalyst-specific supply contracts is small.

ILLUSTRATIVE CLAUSE LANGUAGE — PUBLICLY FILED CATALYST SUPPLY AGREEMENT

> *"WITHOUT LIMITING THE GENERALITY OF THE FOREGOING, CUSTOMER ASSUMES ALL RISK AND LIABILITY FOR THE RESULTS OBTAINED BY THE USE OF ANY GOODS IN THE PRACTICE OF ANY PROCESS, WHETHER IN TERMS OF OPERATING COSTS, GENERAL EFFECTIVENESS, SUCCESS OR FAILURE, AND REGARDLESS OF ANY ORAL OR WRITTEN STATEMENTS MADE BY SUPPLIER, BY WAY OF TECHNICAL ADVICE OR OTHERWISE, RELATED TO THE USE OF THE GOODS."*
>
> *"IN NO EVENT SHALL EACH PARTY'S AGGREGATE LIABILITY ARISING OUT OF OR RELATED TO THIS CONTRACT … EXCEED THE TOTAL OF THE AMOUNTS PAID AND AMOUNTS ACCRUED BUT NOT YET PAID TO SUPPLIER PURSUANT TO THIS CONTRACT IN THE ONE (1) YEAR PERIOD PRECEDING THE EVENT GIVING RISE TO THE CLAIM."*
>
> Source: Catalyst Supply Agreement filed as Exhibit 10.23 to SEC Form 10-K, Plastic2Oil Inc. / EcoNavigation LLC (effective 2 January 2015), publicly accessible via SEC EDGAR. Capitalisation reflects the original document. Cited as illustrative of the assumption-of-risk and aggregate-cap mechanics described above; major catalyst suppliers' standard terms vary in detail but follow the same structural logic. The language remains current: the same limitation-of-liability architecture — aggregate cap at amount paid for the product, exclusion of consequentials, customer assumption of risk — appears in materially identical form in the chemical supply agreement filed as Exhibit 10.11 to the Union Carbide Corporation FY2023 Form 10-K (SEC EDGAR, filed February 2024) between Dow Chemical Company and Union Carbide. This is industry boilerplate, not a 2015 artefact.

4.2 Where the Money Actually Comes From When Beds Fail

The catalyst supply contract is rarely the source of recovery. In contested cases — and specialist forensic engineering firms such as Baker & O'Brien report frequent expert-witness engagements on exactly these disputes — the funds flow tends to follow a different path. First-loss recovery typically comes from the operator's own property damage and business interruption insurance, subject to a deductible that is itself frequently in seven figures. Subrogation by the insurer, where it occurs, targets the process-chemical supplier (not the catalyst supplier) if a specific contaminant can be evidentially traced to an external chemical source. Where the contamination is internally caused — operator error, inadequate guard bed monitoring, failure to specify antifoam grade — recovery is limited to insurance net of deductible. The catalyst supplier, in this architecture, almost never pays the operator's loss.

4.3 The Process-Chemical Supplier as the Real Counterparty

The under-discussed point is that the most economically meaningful liability counterparty for a poisoned catalyst bed is often the process-chemical supplier — not the catalyst supplier. A polydimethylsiloxane-based antifoam introduced into a coker, a recycled solvent batch contaminated with silicon, a corrosion inhibitor that releases organic phosphates downstream, a cleaning chemical with a residual that should not be there: these are the actual triggers in most catalyst-poisoning incidents. Process-chemical suppliers (FQE Chemicals and Crystaphase among others publish on this directly) market explicitly on the absence of catalyst-poisoning species in their formulations. The warranty, the technical data sheet, and the certificate of analysis on a process chemical are therefore as commercially material to a catalyst owner as the catalyst supply contract itself — and the operator's contract architecture should reflect this.

Operators with mature procurement frameworks now require process-chemical suppliers to warrant absence of named poisons (silicon as polysiloxane, organic phosphorus, organic halides), to supply batch-level certificates of analysis, and to accept liability for downstream catalyst impairment if a supplied chemical is shown by independent forensic analysis to be the contamination source. This is not standard practice — it is best practice. The middle of the market still operates with generic safety data sheets, no downstream-impact warranty, and no batch traceability beyond regulatory minimums.

5 Risk-Sharing Models: How Smart Operators and Suppliers Share Exposure

Outright purchase is the historical default. It is rarely the structural optimum. Across the catalyst supply industry, four distinct risk-sharing structures have matured into credible alternatives. Each redistributes economic exposure between supplier and operator differently. None eliminates risk; each changes who carries what.

Model	Mechanism	What It Solves	What It Does Not Solve
Precious-metal leasing	Operator leases (rather than buys) PGMs in catalyst formulations. BASF ECMS, Evonik, Topsoe, and Johnson Matthey all offer this as a structured product.	Removes USD-denominated PGM inventory from the operator's balance sheet. Transfers PGM price risk to lessor or to a managed pool. Aligns metal ownership with metal recovery (closes the loop).	Lease rates spike when PGMs go into deficit (palladium reached 22% lease rates in 2018). Doesn't address poisoning — only the metal value, not the support or activity.
Consigned inventory	Catalyst supplier holds inventory at or near the operator's site under consignment terms; payment triggers only on actual draw-down for use.	Reduces working capital tied up in spare beds. Eliminates obsolescence risk on operator's side. Enables faster bed change-outs.	Assumes operator's storage and handling meet supplier specs. Disputes over draw-down accounting are common.
Performance guarantees	Supplier guarantees catalyst activity, cycle length, or specific KPIs against stated feedstock specifications. Failure triggers credit, replacement, or fee adjustment.	Aligns supplier incentives with operator outcomes. Makes the supplier's technical service team financially material to the operator's run plan.	Guarantees are conditional on feedstock conformance. Supplier exits when feed exceeds specification — which is precisely when the operator most needs the guarantee.
Regeneration / reclaim	Spent catalyst returned to supplier or third-party reclaimer for thermal or chemical regeneration; PGMs recovered and re-credited to operator account.	Cost savings of 40–60% versus fresh catalyst (PatSnap, 2025). Closes the metal loop. Reduces virgin material consumption and carbon footprint.	Regenerated catalyst typically has lower start-of-run activity. Repeated regeneration accumulates fatigue. Not viable for permanently poisoned beds.
Catalyst-as-a-service	Supplier provides catalyst plus full technical service plus performance monitoring as bundled package. Topsoe and Honeywell digital platforms enable this model.	Bundles risk transfer with operational data integration. Supplier sees the actual operating envelope and can react to upsets faster than the operator.	Data-sharing arrangements raise operational confidentiality concerns. Lock-in to a single supplier's monitoring stack reduces switching flexibility.
Process-chemical absence warranty	Process-chemical supplier warrants absence of named catalyst poisons (silicon, phosphorus, halides) in the supplied chemical and accepts downstream responsibility on evidentiary trace-back.	Targets the actual contamination source. Creates a cost of carelessness for process-chemical suppliers.	Few process-chemical suppliers will sign such warranties without a price premium. Forensic trace-back can be technically contested.

Sources: BASF Environmental Catalysts and Metal Solutions; Evonik Precious Metal Management; Topsoe and Honeywell digital service offerings; United Catalyst Corporation lease-rate commentary; PatSnap regeneration market analysis (Aug 2025).

5.1 Why PGM Leasing Is Now the Default for Major Refiners

Platinum group metal leasing has moved from an exotic financial product to standard operating practice for refiners running PGM-loaded units. The economic logic is direct. A typical CCR reformer charge can hold 8,000 to 15,000 troy ounces of platinum and rhenium; at 2025 platinum prices (which surged approximately 92 percent during the year per industry reporting), this is a USD 8–15 million inventory item that is essentially idle for the duration of the catalyst cycle. Leasing converts this from an asset to a periodic operating expense, and — critically — transfers the metal-price risk to a counterparty whose business model is to manage that risk at scale.

BASF's Environmental Catalysts and Metal Solutions group, Evonik's Precious Metal Management service, and the trading desks at Johnson Matthey all offer this as a structured product with leases, consignments, pool accounts, and forward pricing available. The CME Group's commentary in late 2025 notes that oil and gas firms are increasingly using exchange-traded platinum derivatives to hedge plant-expansion and decommissioning exposures, and that there is meaningful PGM inventory locked up in petroleum refining processes that operators are now actively managing rather than passively holding.

6 Competitive Landscape: Winners, Losers, and Why

The catalyst industry is not one industry. It is at least three: bulk refinery and petrochemical catalysts (oligopolistic, technology- and scale-driven), specialty catalysts and process licensing (high-margin, IP-driven), and emission control catalysts (PGM-intensive, OEM-locked, going through the largest single structural change in its history with electric vehicle penetration). The competitive dynamics differ at each layer, and so do the winners.

6.1 The Refinery Catalyst Oligopoly

The fluid catalytic cracking catalyst market — by share of value the most concentrated single sub-segment of the refinery catalyst market — is held by four players: Grace Catalysts Technologies, BASF, Albemarle, and Sinopec, who together hold over 74 percent of global market share according to Intel Market Research (December 2025). BASF leads the broader petroleum cracking catalyst market with an estimated 18 percent revenue share. Hydroprocessing is more fragmented but still dominated by Albemarle, BASF, Topsoe, Honeywell UOP, and Shell Catalysts & Technologies through Advanced Refining Technologies (ART, the Chevron-Grace joint venture).

Player	HQ	Position / Strength	Competitive Move
Honeywell UOP / JM Catalyst Tech	US (UOP) / UK (JM)	Process licensing + catalyst integration. UOP's installed base in refining and petrochemicals is the deepest in the industry.	Acquired Johnson Matthey Catalyst Technologies; deal value adjusted from £1.8 B to £1.325 B (Feb 2026); expected close H1 2026. Adds ~1,900 employees and JM's low-emission fuels, blue hydrogen, blue ammonia, e-methanol pipeline.
Grace Catalysts Technologies (W. R. Grace)	US	Largest FCC catalyst share. ART joint venture with Chevron in hydroprocessing. ACHIEVE, DAVICAT, FUSION brand stack.	Latest FCC platform reportedly improves hydrothermal stability by 22% — material in heavy and metals-laden feeds.
BASF (Refinery Catalysts)	Germany	Broadest portfolio: hydrocracking, hydrotreating, reforming, FCC. Digital twin platforms and PGM trading desk.	Sold FCC catalyst business to Clariant in 2023 (refocusing on petrochemicals and emission catalysts); active in e-methanol with Envision Energy partnership.
Albemarle (Ketjen)	US	Hydroprocessing + FCC dual play. Ketjen brand for specialty catalyst solutions.	USD 45 M multi-year hydrocracking contract for IOC Panipat expansion (Mar 2025). Cobalt cost exposure managed through formulation moves toward NiW.
Topsoe	Denmark	Hydroprocessing, ammonia, methanol, SAF leadership. SOEC electrolyser plant under construction in Herning.	MK-417 SUSTAIN catalyst for biogenic e-methanol; selected by NXTClean Fuels for Port Westward — at 50,000 bpd, the largest greenfield SAF project in the US.
Clariant	Switzerland	CATOFIN propane dehydrogenation, polymer catalysts, FCC (post-BASF acquisition).	StyroMax UL-100 with Technip Energies (Apr 2025) — ultra-low steam-to-oil ratio styrene catalyst; AddWorks titanium-based polyester polymerisation catalysts (K 2025).
Axens	France	Process licensing + catalyst, integrated with IFP Energies nouvelles.	Strong in Middle East and Indian refinery expansion projects.

Player	HQ	Position / Strength	Competitive Move
Shell Catalysts & Technologies	Netherlands	Hydrocracking and gasification catalysts; integrated technology + catalyst offer.	Continued Asia-Pacific footprint expansion.
Sinopec Catalyst Co.	China	Dominant Chinese FCC and hydroprocessing supplier; benefits from domestic refining scale and silicon metal supply.	Sulfur removal capabilities reportedly improving year-on-year (2025); expanding international export.
Evonik Catalysts	Germany	Hydrogenation, fine chemicals, custom catalysts. Closed-loop PGM management.	Specialty catalyst lines and bespoke development for pharma / fine chemicals.

Sources: Intel Market Research (Dec 2025); MarketsAndMarkets (2026); Honeywell press releases (May 2025, Feb 2026); Johnson Matthey FY24/25 results; Polaris Market Research (2024); Future Market Insights (Feb 2025); company press releases.

6.2 Who Is Winning, Who Is Left Behind, and Why

Three structural forces are sorting the field. The first is integration: process licensing combined with catalyst supply — the UOP and Topsoe model — captures more value than catalyst supply alone, and the Honeywell–JM deal extends this logic decisively. Pure catalyst manufacturers without licensing exposure (or without a digital service wrapper) compete primarily on price and risk losing ground in renewable fuels and low-carbon process technologies where the licensor relationship is the dominant entry.

The second is the energy transition. Players with credible green hydrogen, e-methanol, SAF, and CO_2-utilisation portfolios — Topsoe most explicitly, Honeywell-JM by acquisition, BASF through Envision and thyssenkrupp Uhde collaboration — are converting refinery transition capex into multi-year revenue streams. Players whose portfolio is anchored in conventional refining without a transition story face a multi-decade wind-down trajectory in the OECD even as Asian and Middle Eastern volumes hold up.

The third is geopolitics. Sinopec's domestic position is structurally protected by China's silicon metal and rare-earth supply. Western suppliers' exposure to Chinese feedstock and to South African PGM concentration creates material price and availability risk that is increasingly being priced into long-term contracts. The Guangzhou Futures Exchange launched physically-settled platinum and palladium futures contracts on 27 November 2025 — uniquely accepting platinum sponge (the form catalyst manufacturers actually consume) for physical delivery. This is a structural shift in how the metal layer of the catalyst industry is priced and delivered, not just hedged. We discuss the procurement implication for Western buyers in Section 8.3.

7 The AI Question: From Hype to Operational Use

Artificial intelligence in catalysis covers two distinct application stacks, and operators should not confuse them. The first is catalyst discovery: machine-learning models that predict adsorption energies, screen candidate materials, and propose new compositions. This stack is academic-research-heavy, accelerating, and has not yet produced a meaningful share of the industrial catalyst portfolio in active commercial deployment. The second is catalyst operation: digital twins, performance monitoring, deactivation prediction, and unit optimisation that extend run length and improve yield. This stack is in active commercial deployment with documented operational impact.

7.1 What Is Already in Commercial Use

Application	Provider / Tool	Documented Impact
Catalyst deactivation prediction	Topsoe and Honeywell ML platforms (per Mordor Intelligence, 2026; vendor-reported)	Reported extension of catalyst service life by up to 15 percent while maintaining unit reliability. Translates directly to cycle-length and turnaround calendar savings. Note: this figure is a vendor-reported / industry-analyst aggregate; independently audited operational data is not in the public domain.
Industrial AI assistant	Honeywell Forge / Industrial AI Assistant (2025–2026)	Generative AI integration with performance-monitoring layer for operator task automation and troubleshooting. Expanded Honeywell Digital Prime ecosystem went live for customers in Q4 2025.
Digital twin / process optimisation	BASF refinery catalyst digital twin platforms; KBC (Yokogawa); Cognite	Real-time matching of feedstock properties to catalyst loadings and operating conditions. Used for adaptive control and to flag deviation early enough to intervene before deactivation accelerates.
AI-assisted catalyst R&D; (open data)	Open Catalyst Project (Meta FAIR + academic consortium); OCx24 dataset (Nov 2024)	Combines large-scale density-functional theory calculations with experimental validation specifically at industrially-relevant conditions, targeting green hydrogen and CO_2 upcycling. Public dataset under Creative Commons license.
Universal ML interatomic potentials	Academic and supplier-side R&D; (Angewandte Chemie review, 2026)	Replacing trial-and-error catalyst screening with computational property prediction. Industrially relevant for narrowing experimental search space; not yet at production-decision quality for most reactions.
Inverse design / generative models	ScienceDirect review (May 2025); academic partnerships with industry labs	Generative AI proposing new catalyst compositions for target reactions. Frontier research; emerging early commercial pilots in pharma and specialty chemicals.

Sources: Mordor Intelligence Refining Catalysts report (Feb 2026); Honeywell press releases (Feb 2025); Digital Refining catalogues; Open Catalyst Project (FAIR Meta / U Toronto / CMU, Nov 2024); Pisal et al. (arXiv 2412.13838, 2024); Angewandte Chemie review on AI in catalyst materials discovery (Apr 2026).

7.2 What AI Cannot (Yet) Do for the Operator

Two limits are worth stating clearly. First, the AI deactivation-prediction stack is trained on operating data — feedstock composition, temperature, pressure, conversion, yield. It is poor at predicting events outside the training distribution: a novel process-chemical contamination, a feedstock blend the model has not seen, an upstream antifoam swap. The 15 percent life extension figure is from steady-state operation; it does not protect against catastrophic poisoning events, which remain the highest-value liability exposure.

Second, AI-driven catalyst design is producing genuine breakthroughs in academic literature — single-atom catalysts identified in hours rather than months, MOF-derived electrocatalyst architectures with mass activity 70-fold higher than commercial platinum-on-carbon in specific test conditions — but the industrial translation gap remains substantial. Catalyst manufacturing scale-up, long-term stability under industrial conditions, regulatory approval, and contract qualification timelines run on different clocks than computational screening cycles. Operators evaluating AI-derived catalysts should expect a five to ten year timeline from credible academic publication to commercial supply contract.

7.3 A Contractual Recommendation: Require Out-of-Distribution Detection

The operationally useful response to the training-distribution limit above is to require **out-of-distribution (OOD) detection** as an explicit deliverable in any AI service contract or digital-twin licence. An OOD-aware model does not silently extrapolate when it encounters input it was not trained on; it raises a flag — typically as a confidence score, a Mahalanobis distance metric, or an explicit "input outside training distribution" alert — and the operator can then fall back to manual oversight, additional sampling, or precautionary slate-down. Without OOD detection, the same model that delivers steady-state accuracy will produce confidently wrong predictions in exactly the conditions that matter most for liability: a novel antifoam, a new feedstock blend, an upstream chemical-supplier change, an unfamiliar opportunity crude. Practical contract language should specify (a) that the AI service includes documented OOD detection on the production model, (b) what the operator-visible alert mechanism is, (c) what data conditions trigger the alert, and (d) what the documented response protocol is. Vendors that decline to commit to these terms are quietly disclaiming responsibility for exactly the failure mode the platform was procured to prevent.

8 Supply Chain Pressure: PGMs, Critical Minerals, and Geopolitics

Catalyst supply chains are concentrated upstream in ways that the catalyst contract language rarely fully addresses. Force majeure clauses cover gross disruption; they do not cover the sustained price and availability risk that has now become the modal operating condition for several catalyst feedstocks.

8.1 The Critical Layers

Material	Geographic Concentration	2024–2025 Movement	Catalyst Implications
Silicon metal (metallurgical grade)	China: ~70–80% of global output	2021–22 price crisis from Chinese power rationing drove silicon metal up 250–300% and disrupted silicone supply chains.	Direct input to silicone-based process aids and antifoams; indirect input to many catalyst supports.
Platinum	South Africa: >70% global primary supply; 90% of resources	Up ~92% in 2025 (industry reporting). Structural deficit; mine ramp-ups expected in 2026 but supply remains tight.	CCR reformer, hydrocracking, fuel cells, electrolysers, automotive TWC. China holds >95% import dependency; designated platinum a strategic critical mineral in 2025.
Palladium	Russia, South Africa concentrated	Up ~65% in 2025; geopolitical exposure to Russian supply via Hong Kong route (disrupted from July 2024).	Automotive TWC (gasoline). BEV displacement is structural demand drag — partly offset by BEV-credit removals and palladium substitution back from platinum.
Rhodium	South Africa-dominated	Up ~79% in 2025; market shifting from deficit to small surplus per Heraeus 2026 forecast.	NOx control in TWC; specialty chemical catalysts; glass manufacturing.
Ruthenium	South Africa primary; China dominates downstream chemical use	Up ~35% by Q1 2025; strong electronics + chemicals demand.	Caprolactam (nylon precursor) catalyst, Cativa acetic acid process, single-atom catalysts, hydrogen evolution.
Iridium	South Africa-dominated; very limited supply	Tight supply; PEM electrolyser scaling is the new structural demand pressure.	PEM electrolyser oxygen evolution catalyst — and there is no known earth-abundant drop-in. Critical bottleneck for green hydrogen scale-up.
Cobalt	DRC: ~75% of mined supply	DRC export ban (Feb 2025) replaced by quotas; prices up 65–170% from 2024 lows; USD 21,500 → USD 48,500/t through Oct 2025.	CoMo hydrotreating catalysts (sulfur removal). Cost pressure pushing operators toward NiW formulations.
Nickel	Indonesia: ~50% of mined supply (rising)	Indonesian quota cuts >30% since Sep 2025; nickel up 35% to USD 19,138/t early 2026.	NiMo and NiW hydroprocessing catalysts; methanation; ammonia synthesis. Battery demand is the dominant volume driver.
Rare earths (Ce, La)	China: ~85% refining concentration	Persistent geopolitical risk; export licensing tightening (rare earth controls as part of broader Chinese export-control regime).	FCC catalyst rare-earth content. Some FCC catalysts now formulated rare-earth-free to mitigate exposure.

Sources: Heraeus Precious Forecast 2026; Johnson Matthey PGM Market Report 2025 (May 2025); USGS Mineral Commodity Summaries; IEA Global Critical Minerals Outlook 2025; Crux Investor (Dec 2025); Investing News Cobalt Market Update (Jan 2026); First Atlantic Nickel disclosures (citing Goldman Sachs); World Platinum Investment Council.

8.2 What This Means for Catalyst Buyers

Three implications follow. First, the metal layer is now the dominant single risk factor for many catalyst contracts — exceeding feedstock contamination risk for PGM-loaded units. Second, the geographic diversification of catalyst manufacturing has not kept pace with the geographic concentration of upstream mineral supply: a Western supplier with a Chinese silicon dependency, a German hydroprocessing catalyst with DRC cobalt exposure, a Norwegian electrolyser project with South African iridium dependency are all genuinely exposed to upstream policy decisions outside their operating jurisdiction. Third, contract terms of 12–36 months — historically standard — are increasingly being supplemented with metal-pricing clauses, shared escalation mechanisms, and break clauses tied to named geopolitical triggers. Operators not negotiating these explicitly are accepting metal-price risk by default.

8.3 Physical-Delivery Hedging — A New Tool for Procurement

On 27 November 2025, the Guangzhou Futures Exchange (GFEX) launched physically-settled platinum and palladium futures contracts, with options trading from 28 November. Contracts are RMB-denominated, bi-monthly, and — uniquely among major global exchanges — accept both ingot *and sponge* for physical delivery. Sponge is the powder form of platinum that catalyst manufacturers and automotive end-users actually consume; no other major exchange currently offers it as a deliverable grade. GFEX publishes daily warehouse inventory data, providing a level of physical-stock transparency that LBMA and NYMEX do not match. First-day combined turnover was RMB 42.28 billion.

The procurement implication for Western catalyst buyers is concrete. Most Western refiners and chemical operators currently hedge PGM exposure through cash-settled futures (NYMEX), through OTC contracts with their refiner (Heraeus, Johnson Matthey, Umicore), or — increasingly — through metal lease structures. None of these instruments is a substitute for guaranteed access to physical metal in the form actually consumed in catalyst manufacture if cross-border flows are disrupted. The structural sensitivity is well-documented: roughly 70% of South African PGM exports have historically flowed through Hong Kong-based refining and finance hubs into China and global markets, and any disruption to that route — sanctions, capital controls, logistics bottlenecks, or a deterioration in cross-strait conditions — has first-order consequences for Western catalyst makers. **Procurement leads with material PGM exposure should now evaluate whether to add a physical-delivery hedge to their PGM contract portfolio,** using GFEX sponge contracts as one component, alongside NYMEX cash-settled positions, refiner offtake, and the existing metal-lease structures discussed in Section 5. The point is not to replace existing instruments but to add a physical-delivery leg that survives disruption to financial-settlement channels. This is operationally feasible: GFEX accepts deliveries from international suppliers accredited by the London Platinum and Palladium Market, so the qualification process is not exotic.

9 New Technologies: What's Coming, What's Real

Catalyst innovation is happening on at least four parallel tracks: process-side incremental improvement (which dominates revenue), single-atom and atomically-dispersed catalysts (where academic progress is fastest), MOFs and MOF-derived electrocatalysts (where the green-hydrogen application is pulling the field forward), and biocatalysis (which has matured into a mainstream pharma and specialty-chem production technology and is now expanding into bulk applications). Each track has different timelines, different industrial readiness, and different effects on the competitive landscape.

Technology	Industrial Readiness	Strategic Significance
Single-atom catalysts (SACs)	Academic frontier; emerging industrial pilots. Academic mass activity claims very strong (e.g. Ru-Bi single-atom on graphene oxide reported at 72-fold Pt/C in alkaline HER; Pt SAC on MOF-derived carbon).	Maximum atom utilisation efficiency = path to dramatic PGM-loading reduction. Industrial translation hampered by atom agglomeration (Ostwald ripening) under real conditions; reducible-oxide supports such as ceria provide promising anchoring chemistry.
MOF-derived electrocatalysts	Lab-to-pilot. NiRu-BDC and similar MOF systems achieving Pt/C-comparable HER performance in published papers (2025–26).	Direct play on green hydrogen scale-up, where iridium is the bottleneck. If industrial-scale stability is solved, this displaces a meaningful portion of PGM demand in PEM electrolysers.
Biocatalysis (industrial enzymes)	Mature in pharmaceutical APIs; expanding into specialty and bulk chemicals. 2025 Angewandte Chemie review documents commercial-scale enzymatic synthesis of peptide building blocks, rare sugars, oligonucleotides, terpenoids (e.g. Ambrox).	Replaces or supplements heavy-metal catalysis in selected reactions. Mild conditions, high stereoselectivity. Directed evolution and AI-assisted protein engineering accelerating discovery.
Bio-silicone (renewable silicon)	Early commercial — Elkem, Wacker programmes; bio-sourced carbon in silicon-metal smelting (Elkem progressing from 20% to a target 50% bio-carbon share); bio-based carriers and solvents (e.g. Elkem MIRASIL™ N-DML 15, PURESIL™ ORG 02 — high natural-origin content).	Reduces upstream Chinese silicon-metal exposure and the Scope-1 carbon footprint of silicone manufacture. **Important caveat for refinery and petrochemical operators:** the active polysiloxane (PDMS) backbone is chemically identical to the conventional version. Catalyst poisoning — silicon depositing on alumina hydroxyls and Pt sites downstream — depends on the silicon atom and the Si–O linkage, not on the carbon source used to make the silicon metal. Bio-silicone antifoams therefore solve an ESG and supply-chain problem; they do not solve the silicon-poisoning problem. We have not located any published vendor or operator test data demonstrating reduced catalyst carry-over from bio-silicone formulations. Operators procuring bio-silicone antifoams on ESG grounds should request the same downstream-impact warranty discussed in Section 4.3 and the same batch-level certificate of analysis as for conventional product.

Technology	Industrial Readiness	Strategic Significance
Bifunctional cascade catalysts (CO_2-to-fuel)	Demonstration to early commercial. Topsoe Hydro-OLI for SAF; Haru Oni, Synhelion, OXCCU operating units.	Energy efficiencies of 21–57% for direct CO_2-to-jet pathways reported. Material to the EU ReFuelEU and US SAF tax credit policy frameworks; commercial scale depends on green hydrogen cost.
Rare-earth-free FCC	Commercial. Already in field deployment as one supplier-side response to rare-earth supply risk.	Reduces FCC catalyst exposure to Chinese rare-earth concentration. Performance trade-offs on activity / metals tolerance — formulator-specific.
Cobalt-free hydroprocessing (NiW)	Commercial; expanding share. Mordor Intelligence (2026) reports growing cobalt-free NiW formulations to mitigate cobalt cost volatility.	Direct response to DRC cobalt cost shocks. Activity matched in many duty profiles; still trade-offs in deep desulfurisation severity.

Sources: PMC reviews on cobalt-based and Pt-based single-atom catalysts (2025); MOF-derived single-atom electrocatalyst review (Jan 2026); Bayer et al. (Angewandte Chemie, May 2025) industrial biocatalysis update; RSC Sustainable Energy & Fuels review on CO_2-to-SAF (Oct 2025); Topsoe technical materials; Mordor Intelligence (2026).

10 Forward View: Risks, Opportunities, and What to Watch

Risk / Opportunity	Horizon	Detail
Process-chemical liability re-architecture	Short — 2026–2027	Operators with mature procurement now require process-chemical suppliers to warrant absence of named catalyst poisons and accept downstream impairment liability. This becomes increasingly standard as forensic trace-back capability improves and insurers demand it.
PGM leasing as default for PGM-loaded units	Short — already underway	Balance-sheet logic + price volatility makes leasing structurally attractive. BASF, Evonik, Topsoe, Johnson Matthey all offer this. Operators not on a leasing structure for PGM-loaded units are accepting metal-price risk for no operational benefit.
Honeywell-JM integration completion	Short — H1 2026 close	Adjusted deal value of £1.325 B (Feb 2026) reflects diligence and market reassessment. Once closed, creates the largest integrated process-licensing-plus-catalyst player in refining and petrochemicals — and accelerates the consolidation pressure on remaining independent licensors.
AI deactivation-prediction adoption	Short — active deployment	Topsoe and Honeywell digital service offerings now include ML deactivation prediction. The 15% life extension figure is steady-state; the operational value is in catching upset trajectories before they become bed losses. Procurement teams should require **out-of-distribution detection** in AI contracts (Section 7.3) so the platform flags rather than silently extrapolates when conditions move outside the training set.
GFEX physical-delivery PGM hedging	Short — already trading	Guangzhou Futures Exchange platinum and palladium futures launched 27 November 2025 with sponge as a deliverable grade — a tool no other major exchange offers. Western catalyst makers and end-users with material PGM exposure should evaluate adding a physical-delivery leg to their hedging portfolio (Section 8.3) alongside existing cash-settled NYMEX positions and metal-lease structures.
California / EU rare earth and PGM policy	Short–medium — ongoing	Critical minerals policy on both sides of the Atlantic is shifting from rhetorical to operational. Catalyst supply chains with concentrated upstream exposure should expect contract clauses around supply assurance and origin documentation as standard practice, not premium.
Green hydrogen / e-fuel catalyst market	Medium — 3–7 years	Project pipeline (NXTClean, ITC-WasteFuel, Topsoe SOEC, BASF e-methanol with Envision, M2SAF with thyssenkrupp Uhde) creates multi-billion-euro catalyst demand. Iridium scarcity is the single largest scale-up bottleneck; SAC and MOF-derived alternatives are the decisive R&D; race.
Biocatalysis displacement of heavy-metal routes	Medium — 5–10 years in specific reactions	Pharmaceutical APIs are largely converted; specialty chemicals are converting; bulk chemicals follow on a longer arc. Implications for fine-chemicals catalyst suppliers and for selective heavy-metal catalysis are direct.
Circular economy and PGM recovery	Medium — accelerating	Closed-metal-loop services (Evonik, BASF, Topsoe, Heraeus) move from differentiator to expectation. Carbon footprint of recycled PGM is materially lower; recycled supply share is increasingly central to OEM sustainability commitments.
Structural decline of OECD refining	Long — 2030s and beyond	OECD gasoline and diesel demand peaks in mid-2020s. Refinery catalyst demand shifts to Asia, Middle East, India. European refinery survival depends on petrochemical integration, biofuel co-processing, and SAF production — all of which are catalyst-intensive but in different chemistry than the legacy stack.
Cascade poisoning visibility	Immediate	Multi-bed operators (refineries with NHT → CCR → hydrocracker chains) need real-time silicon, sulfur, sodium, arsenic monitoring at intermediate streams — not just at the front end. Current practice is over-reliant on lab samples with multi-day turnaround. Online analyzers (XRF, ICP-MS) close the gap.

Sources: IMP forward analysis; Honeywell investor disclosures (Feb 2026); JM FY24/25 results; Topsoe Annual Report 2025; IEA Global Critical Minerals Outlook 2025; Mordor Intelligence (Feb 2026); industry technical literature.

The defining feature of catalyst liability in 2026 is that the value-at-risk is increasing while the contractual architecture lags. The catalyst itself is becoming more capital-intensive (PGMs up 65–92 percent in 2025), the cost of failure is increasing (turnaround costs, lost-production day rates), and the failure modes are becoming more numerous as feedstock blends widen and process chemicals diversify. Standard supply contracts have not adjusted. The operators who will protect their balance sheets in the next decade are those who treat catalyst liability not as a procurement matter but as a structured risk-management exercise spanning supplier selection, process-chemical specification, insurance architecture, leasing strategy, and digital monitoring integration. The cost of not doing this — borne in unbudgeted outages and uncovered bed losses — is rising faster than the cost of doing it. The question for any operator is no longer whether the catalyst contract is sufficient (it is not), but which of the available risk-sharing structures fits the asset.

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