INDUSTRIAL AND PRODUCTION ENGINEERING

Asset Integrity Management and Design: Engineering Bankable, Resilient Pipeline Infrastructure for Nigeria

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Abstract

Asset Integrity Management (AIM) converts pipeline engineering assurance into investor confidence for resilient Nigerian infrastructure. This paper positions AIM as a bankability framework that enables Green Bonds, Sustainability-Linked Loans, Public-Private Partnerships and Development Finance Institution funding by translating integrity performance into auditable lender-grade evidence. It links design gates, risk-based inspection, corrosion control, digital monitoring, emergency readiness and host-community engagement to financeable KPIs such as ILI completion, cathodic protection compliance, anomaly closure, uptime, ROW security and integrity OPEX discipline. The paper further addresses key financier concerns—regulatory uncertainty, foreign-exchange volatility, deferred maintenance and community disruption—by showing how robust AIM supports predictable lifecycle OPEX, stronger debt-service confidence, lower Levelized Cost of Transportation and reduced unplanned downtime. It concludes that Nigeria can unlock cheaper, longer-tenor capital for pipelines when technical integrity, social licence and financial governance are integrated as one evidence-based enterprise value system for national energy security and sustainable economic growth.

Keywords: asset integrity management; pipeline design; risk-based inspection; corrosion control; Nigeria; pipeline finance; resilience; digital twins; API RP 1160; host communities

1 Introduction: from pipeline construction to pipeline bankability

Nigeria's pipeline infrastructure is not merely steel buried in soil or laid across rivers, swamps and offshore corridors. It is a national balance-sheet asset: a conduit for crude oil export earnings, domestic gas supply, power generation, industrialisation, refinery feedstock, compressed natural gas expansion and regional energy diplomacy. In this context, Asset Integrity Management and Design must be understood as a financial discipline expressed through engineering controls.

The Nigerian regulatory environment already recognises this linkage. The Nigeria Upstream Petroleum Regulatory Commission (NUPRC) guidelines cover routing, materials, construction quality, pressure systems, operations, maintenance, integrity management and decommissioning expectations [4]. NUPRC also identifies facility integrity, asset reliability, conformity assessment, licence-to-operate and risk-based inspection as core regulatory functions [5]. These are not administrative details; they are signals to financiers that pipeline projects require technical governance across the asset life cycle.

Recent Nigerian experience reinforces the point. Reporting on improved pipeline surveillance and security described a sharp recovery in the share of crude reaching export terminals following coordinated operational and security interventions [35]. The lesson is important but should not be

overstated: improved availability can strengthen cash-flow predictability, yet reported throughput gains are not, by themselves, proof of sustained integrity performance. That proof requires auditable inspection, anomaly-closure, environmental and operating data.

2 Conceptual thesis: integrity is a form of capital protection

The central thesis of this article is that AIM converts engineering assurance into financial confidence. A pipeline project may have reserves, tariffs and demand, but without demonstrable integrity it carries hidden liabilities: spills, shutdowns, product theft, regulatory sanctions, community conflict, repair backlogs, insurance exclusions, delayed debt service and reputational loss.

API RP 1160 frames pipeline integrity as a systematic process for safe operation, risk assessment and management throughout the operating life of hazardous-liquid pipelines [1]. DNV-RP-F116 provides complementary system-level guidance for submarine pipeline integrity management [3]. Recent synthesis shows that risk-based AIM is moving from qualitative prioritisation toward data-supported and machine-learning-assisted inspection planning, while expert judgment and data quality remain decisive [9]. Applied to Nigeria, these sources imply that a bankable pipeline is not simply the cheapest pipeline to build; it is the pipeline whose risks are understood, designed against, monitored and continuously reduced.



Figure 1. Asset integrity as the bridge between engineering and capital.

3 Nigerian context: why AIM must be designed for local realities

Nigeria's pipeline environment is technically complex. It includes swamp terrain, river crossings, coastal exposure, urban encroachment, corrosion-prone soils, ageing assets, illegal connections, third-party interference, security threats and climate-driven flooding. Under the Petroleum Industry Act framework, regulatory responsibilities are distributed across upstream and midstream/downstream institutions, while licensing, environmental compliance, open access and pipeline transportation requirements shape the project risk profile [4, 35].

Nigeria also depends heavily on gas infrastructure for power, industrial use and domestic energy-transition objectives. Current legal and regulatory analysis identifies major gas transportation systems and continuing private-sector infrastructure development [35]. For these assets, integrity cannot be retrofitted only after failures occur; it must be embedded from concept selection through design, procurement, construction, commissioning, operation, life extension and decommissioning [4, 7].

Table 1. Nigeria-specific integrity threats and design responses.

Integrity Threat	Nigerian Manifestation	Design Response	AIM Response	Financing Relevance
External corrosion	Wet soils, swamp terrain, coastal salinity, coating damage	High-performance coating, cathodic protection, AC/DC interference assessment	CP surveys, close interval potential surveys, corrosion growth modelling	Reduces spill liability and unplanned shutdown risk
Internal corrosion	Water dropout, CO_2/H_2S, poor dehydration, microbial activity	Material selection, corrosion allowance, pigging facilities, inhibitor injection	Fluid sampling, corrosion coupons, intelligent pigging, inhibitor performance tracking	Supports predictable maintenance reserve planning
Third-party damage	Illegal connections, excavation, vandalism, encroachment	Deeper burial, concrete slabs, marker posts, block valves, fibre-optic sensing	ROW patrols, drones, community surveillance, security integration	Protects throughput and debt-service cash flow
Geotechnical hazards	River scour, erosion, landslide-prone corridors, floodplains	HDD crossings, burial depth, geohazard mapping, slope stabilisation	River crossing inspection, bathymetry, strain monitoring	Reduces catastrophic rupture and repair CAPEX
Operational overpressure	Compressor trips, valve closures, hydraulic surge	Surge analysis, pressure relief, ESD philosophy, control logic validation	Alarm management, proof testing, pressure excursion tracking	Demonstrates operational discipline to insurers
Ageing and fatigue	Legacy pipelines, unknown records, repair history gaps	Fitness-for-service design and life-extension criteria	Integrity data reconciliation, anomaly dig programme, reassessment intervals	Enables refinancing and asset-life extension
Cyber-physical risk	SCADA intrusion, telemetry manipulation, leak detection compromise	Segmented control architecture, secure communications, redundancy	Cybersecurity audits, incident response drills, access control	Increasingly central to lender and insurer due diligence

Integrity Threat	Nigerian Manifestation	Design Response	AIM Response	Financing Relevance
Community conflict	ROW disputes, sabotage economy, compensation grievances	Social baseline in route selection, access roads, local content planning	Host community engagement, grievance mechanism, benefit-sharing metrics	Converts social licence into project bankability

4 AIM across the pipeline life cycle

AIM begins before the first pipe joint is ordered. It should shape the design basis, route alignment, material class, welding specification, coating system, block-valve spacing, piggability, leak detection philosophy, metering architecture and emergency response assumptions.

NUPRC's official pipeline guidelines explicitly frame pipeline design, construction and operation as an integrated regulatory subject, not separate silos [4]. This is technically consequential because design decisions determine operational risk for decades and constrain later inspection, repair and emergency-response options.

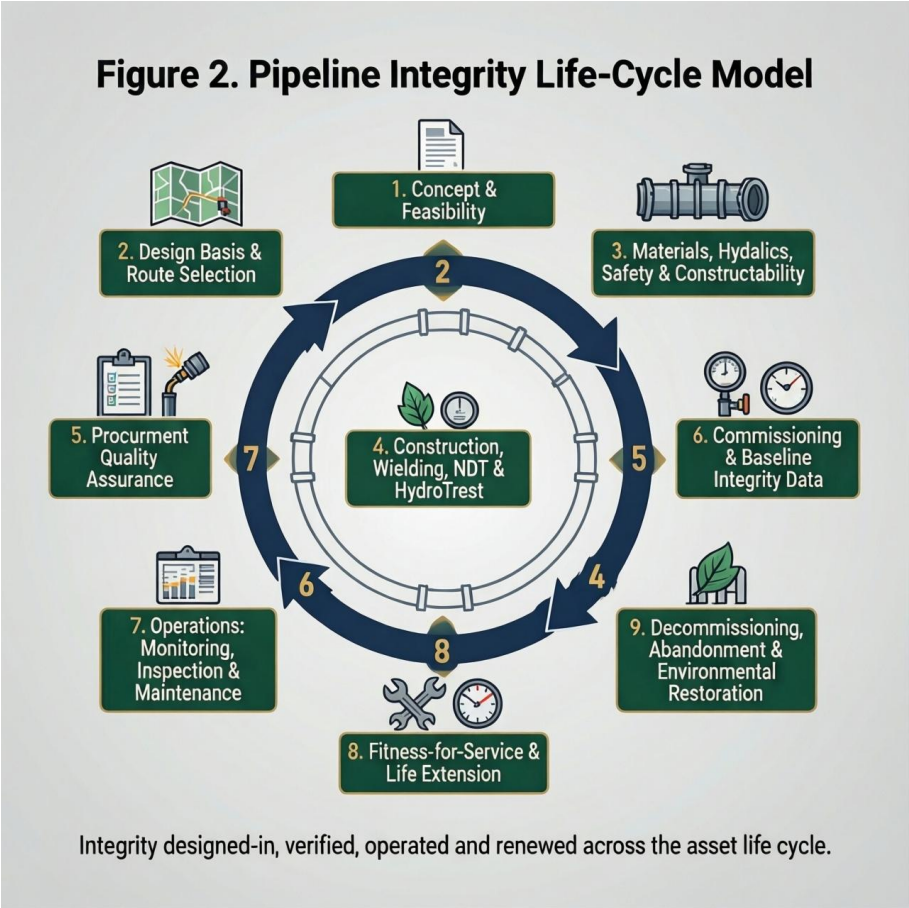


Figure 2. Pipeline integrity life-cycle model.

5 Design for integrity: technical requirements for bankable pipelines

Design for integrity requires more than code compliance. It requires every design choice to be traceable to a threat, a performance requirement, a verification activity and a monitoring method.

The asset-management perspective is consistent with ISO 55000 principles, ISO 31000 risk-management guidance and the updated ISO 55001 management-system requirements [6–8].

5.1 Design basis

The design basis should define product type, pressure envelope, temperature range, flow regime, design life, terrain class, environmental sensitivity, population density, hydraulic transient cases, security assumptions, corrosion mechanisms and emergency isolation philosophy.

A bankable design basis should answer five questions:

1. What can fail?
2. How likely is failure?
3. What are the consequences?
4. Which design barriers prevent failure?
5. Which operational systems prove that the barriers remain effective?

5.2 Route selection

Route selection is the first and most powerful integrity decision. Poor routing creates permanent risk. In Nigeria, route selection should integrate geospatial analysis, geotechnical investigation, hydrology, flood modelling, host-community mapping, security risk assessment, environmental sensitivity and access for maintenance. Early integration of these variables also creates a clearer evidence trail for environmental and social due diligence [27, 30, 33].

5.3 Materials and mechanical design

Materials should be selected not only for pressure containment but also for fracture resistance, weldability, sour-service compatibility, fatigue performance and corrosion resistance. For gas pipelines, fracture-propagation control and crack-arrest philosophy are essential. For crude and multiproduct lines, internal corrosion allowance, piggability and contaminant control are critical. The selected material class should be tied to credible threat mechanisms and to inspection capability, rather than treated as a standalone procurement decision [1–3].

5.4 Constructability and quality assurance

Construction quality is future integrity. Welding procedures, welder qualification, non-destructive testing, coating application, trench padding, lowering-in, backfilling, hydrotesting and as-built documentation determine the future anomaly burden of the asset. A complete, georeferenced construction dossier is therefore both an operational baseline and a lender-facing control record [4, 7].

Table 2. Design integrity gates for pipeline projects.

Project Gate	Key Integrity Deliverables	Decision Question	Evidence Required for Financiers
Gate 1: Concept	Preliminary threat register, route options, social and environmental constraints	Is the corridor technically and socially feasible?	Route risk report, preliminary CAPEX/OPEX risk allowance
Gate 2: FEED	Design basis, corrosion philosophy, HAZID, QRA, class location study	Is the design bankable and licensable?	FEED package, risk register, regulatory compliance matrix

Project Gate	Key Integrity Deliverables	Decision Question	Evidence Required for Financiers
Gate 3: Detailed Design	IFC drawings, material specifications, surge study, CP design, leak detection design	Are all credible threats engineered against?	Independent design review, technical due diligence report
Gate 4: Procurement	Vendor QA/QC plan, mill certificates, coating qualification, valve testing	Are critical components traceable and compliant?	Manufacturing records, inspection release notes
Gate 5: Construction	Welding records, NDT, coating holiday tests, hydrotest, reinstatement evidence	Was the asset built as designed?	Construction dossier, as-built GIS, hydrotest certificate
Gate 6: Commissioning	Baseline inspection, operating limits, emergency response plan, SCADA validation	Is the asset safe to operate?	Commissioning certificate, integrity baseline, operating envelope
Gate 7: Operations	RBI plan, ILI schedule, CP monitoring, anomaly management, KPI dashboard	Is integrity continuously controlled?	AIM dashboard, audit reports, insurer/lender compliance reports
Gate 8: Life Extension	Fitness-for-service, remaining life, revalidation of MAOP/MOP	Can the asset safely operate beyond original life?	Remaining-life assessment, updated risk model
Gate 9: Decommissioning	Abandonment plan, environmental restoration, residual liability closure	Can liabilities be retired responsibly?	Decommissioning fund evidence, closure certificates

6 Risk-based inspection and quantified integrity management

A practical risk-screening relationship is:

$$\text{Risk} = \text{Probability of Failure (PoF)} \times \text{Consequence of Failure (CoF)} \tag{1}$$

This relationship is a prioritisation device, not a substitute for a validated risk model.

The discipline lies in making PoF and CoF evidence-based. For pipelines, PoF is influenced by corrosion rate, defect size, pressure cycling, coating condition, cathodic-protection effectiveness, material properties, geohazards, third-party activity and operational excursions. CoF is influenced by product flammability, release volume, population exposure, environmental sensitivity, repair accessibility, business interruption and reputational impact. Recent reviews emphasise that risk-based inspection improves prioritisation and resource allocation, but model outputs remain sensitive to inspection coverage, defect uncertainty and the quality of failure data [1, 9].

API RP 1160's emphasis on robust risk assessment and integrity systems aligns with this lifecycle approach [1]. DNV-RP-F116 provides complementary guidance for offshore and submarine pipeline segments where inspection access and failure consequences are more complex [3]. Any Nigerian application should document uncertainty, validate assumptions against local operating history and use independent review for high-consequence decisions.

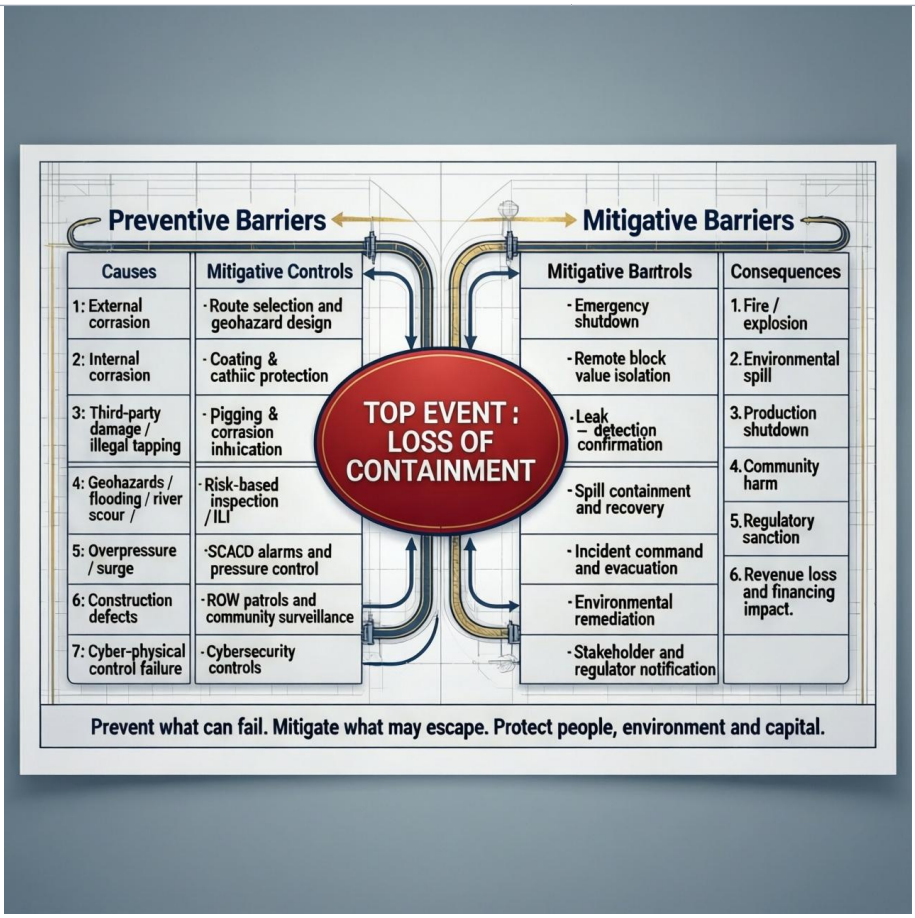


Figure 3. Bow-tie model for pipeline loss of containment.

Table 3. Practical risk matrix for pipeline integrity prioritisation.

Consequence ↓ / Probability →	Rare	Unlikely	Possible	Likely	Almost Certain
Minor	Low	Low	Medium	Medium	High
Moderate	Low	Medium	Medium	High	High
Major	Medium	Medium	High	High	Extreme
Severe	Medium	High	High	Extreme	Extreme
Catastrophic	High	High	Extreme	Extreme	Extreme

Interpretation:

- Low: Manage through routine inspection.
- Medium: Add targeted monitoring and maintenance.
- High: Require engineering review and mitigation plan.
- Extreme: Immediate executive attention, risk reduction or operating restriction.

7 Corrosion management: the central technical pillar

Corrosion remains one of the most persistent pipeline integrity threats. Recent research continues to show a shift from periodic inspection toward continuous or near-continuous monitoring, advanced non-destructive testing and predictive analytics; however, field deployment must address sensor

survivability, calibration, false positives and data governance [9–18]. A world-class Nigerian corrosion-management programme should therefore combine design prevention, operational control and inspection verification.

The corrosion management system should include:

- External corrosion control: coating selection, cathodic protection, soil resistivity testing, CP stations, interference studies and coating surveys.
- Internal corrosion control: dehydration, chemical inhibition, pigging, biocide treatment, corrosion coupons, electrical resistance probes and fluid analysis.
- Microbiologically influenced corrosion: bacterial monitoring, water control and targeted biocide programmes.
- Corrosion under disbonded coating: direct assessment and ILI correlation.
- Data integration: corrosion rates linked to remaining wall thickness, MAOP/MOP and reassessment intervals.

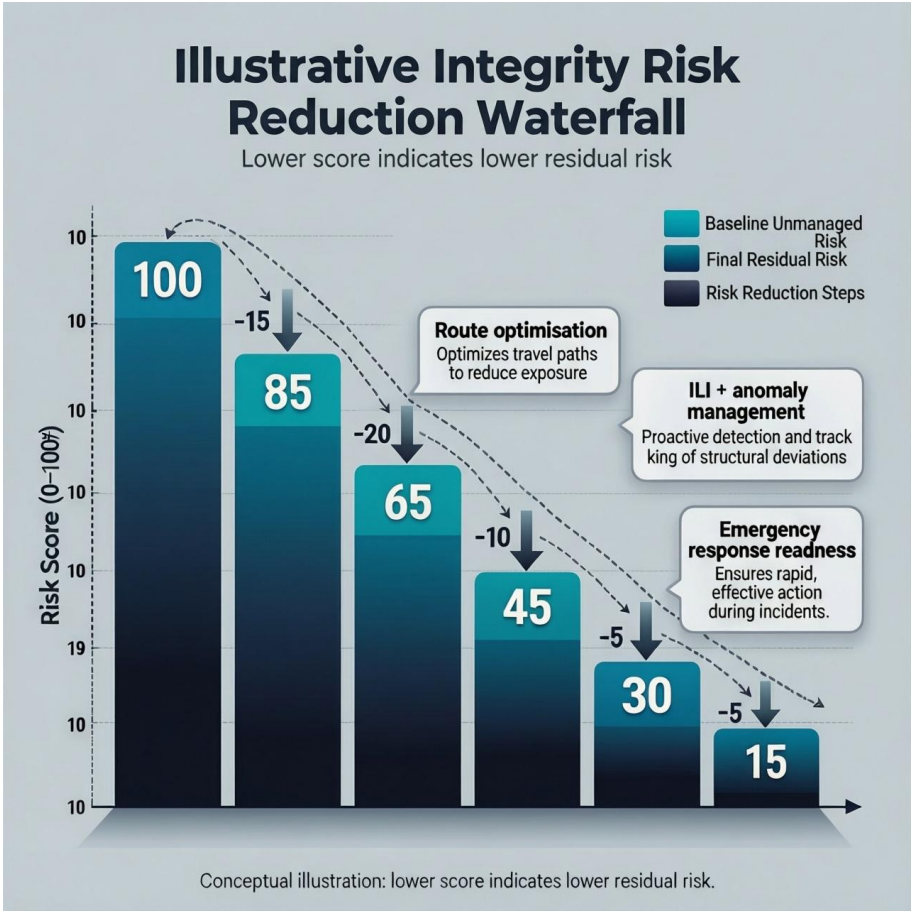


Fig 1. Illustrative integrity risk reduction waterfall.

8 Digital AIM: from inspection files to integrity intelligence

Nigeria's future pipeline systems should be designed with digital integrity from day one. This means the asset must have a governed single source of truth: georeferenced design data, construction records, inspection findings, corrosion readings, CP data, repair history, incident logs, operating excursions and financial-risk indicators. Digital twins are valuable when they connect validated

physical-asset data to models and decisions; they are not a substitute for inspection, engineering judgment or cybersecurity controls [18–21, 34].

Digital AIM should include:

1. GIS-based asset register
2. SCADA and leak detection integration
3. Inline inspection data management
4. Risk-based inspection software
5. Drone and satellite ROW surveillance
6. Fibre-optic distributed acoustic sensing for intrusion detection
7. Digital twin for hydraulic and integrity modelling
8. Cybersecurity controls for operational technology [34]
9. Mobile field reporting
10. Executive integrity dashboard

Table 4. Digital AIM data architecture.

Data Layer	Typical Data	Integrity Use	Financing Use
Asset register	Pipe grade, wall thickness, coating, valves, welds	Defines technical baseline	Establishes asset value and replacement cost
Geospatial layer	Route, crossings, communities, environmental receptors	Supports threat mapping	Supports land, security and ESG due diligence
Operating data	Pressure, temperature, flow, alarms	Detects excursions and abnormal operation	Demonstrates throughput reliability
Inspection data	ILI, CP surveys, coating surveys, NDT	Supports anomaly ranking and repair planning	Provides evidence of maintenance discipline
Maintenance data	Repairs, replacements, pigging, valve tests	Confirms barrier performance	Supports OPEX forecasting
Incident data	Leaks, theft attempts, near misses	Enables root cause analysis	Supports insurance and risk pricing
Community/ security data	ROW patrols, encroachment, illegal taps	Reduces third-party damage	Protects revenue and social licence
ESG data	Methane, spills, remediation, community response	Supports environmental stewardship	Aligns with lender ESG requirements

Technology does not manage integrity; people do. A credible AIM system must define accountability from board level to field technician. NUPRC's mandate includes conformity assessment, facility integrity, standards, technical studies and risk-based inspection, confirming that integrity governance is a regulatory expectation, not merely an internal preference [5]. The three-lines model should also preserve independence between operations, integrity assurance and audit.

Table 5. Three lines of assurance for pipeline AIM.

Assurance Line	Responsible Actors	Core Responsibility	Typical Evidence
First line	Operations, maintenance, field surveillance	Operate within limits; execute inspections and repairs	Daily logs, permits, maintenance records
Second line	Asset integrity, HSE, corrosion, process safety	Set standards, verify risk controls, manage threats	AIM plan, RBI reports, corrosion reviews
Third line	Internal audit, regulator, independent engineer, lender technical adviser	Provide independent assurance	Audit reports, compliance certificates, lender reports

Evidence and limitation: The proposed link between AIM maturity and financing terms is a reasoned framework, not a causal estimate from a Nigerian project dataset. Its practical value is as a due-diligence architecture: it translates engineering controls into evidence that can be tested by lenders, insurers, regulators and communities. Validation should use asset-level performance, incident, inspection, OPEX, downtime and financing data over time [9, 30–32].

9 AIM and financing: converting technical controls into capital access

The conference theme, "Financing the Future," demands that AIM be framed in the language of capital. Financiers assess risk-adjusted cash flows, legal enforceability, environmental and social exposure, and the credibility of project controls—not steel in isolation. Sustainable-infrastructure guidance similarly emphasises quality, resilience, inclusion and transparent risk allocation as conditions for mobilising private capital [30]. Therefore, a resilient pipeline must present integrity evidence in a form that lenders, insurers and investors can evaluate.

A bankable AIM package should include:

- Regulatory compliance matrix
- Independent design review
- Asset integrity management plan
- Risk register and mitigation tracker
- Corrosion management plan
- Emergency response plan
- Security and ROW protection plan
- Host community engagement framework
- Environmental and social management plan
- Digital asset register
- Inspection and maintenance budget
- Insurance loss-control report
- Decommissioning and abandonment cost estimate

Pipeline transportation, environmental compliance and open-access requirements under the Petroleum Industry Act framework directly affect financing because non-compliance can impair licence continuity, tariff recovery, export reliability and debt service [35]. Sustainable-finance instruments

add disclosure and reporting expectations: Green Bond Principles focus on use-of-proceeds transparency, while sustainability-linked instruments require credible, material, measurable and externally verifiable performance targets [31, 32]. AIM KPIs should therefore be selected for materiality and auditability, not merely for ease of reporting.

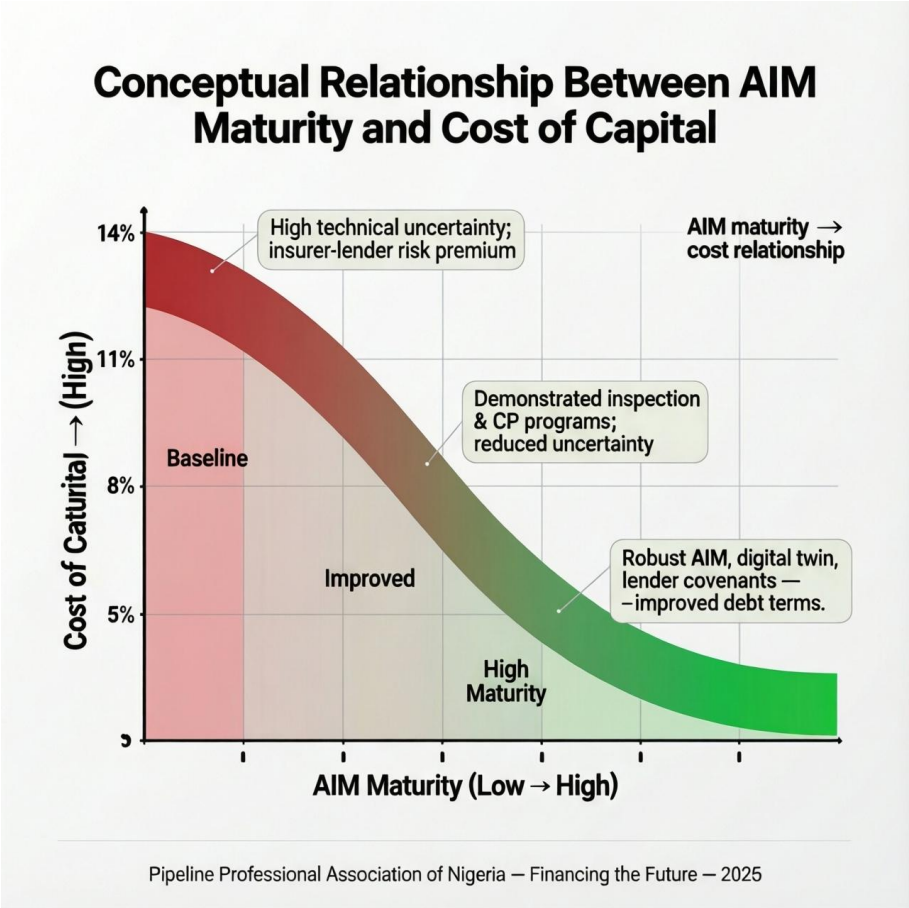


Fig 2. Conceptual relationship between AIM maturity and cost of capital.

Interpretation: As AIM maturity increases, technical uncertainty, environmental liability, outage risk and insurance risk may decline. This can improve lender confidence, although actual pricing depends on macroeconomic, sponsor, regulatory and project-specific factors. The relationship is therefore conceptual rather than a guaranteed causal pricing curve.

Table 6. AIM metrics that should become financing covenants.

KPI	Technical Meaning	Suggested Reporting Frequency	Why It Matters to Capital Providers
Percentage of pipeline covered by current risk assessment	Measures integrity knowledge	Quarterly	Shows whether risk is actively governed
CP compliance rate	Indicates external corrosion protection	Monthly/Quarterly	Reduces corrosion-related failure risk
ILI completion versus plan	Confirms inspection discipline	Quarterly/Annually	Supports anomaly management confidence
High-risk anomaly closure rate	Tracks repair execution	Monthly	Prevents backlog-driven failures

KPI	Technical Meaning	Suggested Reporting Frequency	Why It Matters to Capital Providers
Number of pressure excursions outside operating window	Measures process control	Monthly	Indicates operational discipline
Leak detection system test success rate	Confirms detection readiness	Quarterly	Reduces loss-of-containment consequence
Emergency response drill completion	Confirms response capability	Semi-annually	Reduces consequence severity
ROW encroachment and illegal tap events	Tracks third-party threat	Monthly	Protects throughput and revenue
Methane/spill incident rate	Measures ESG performance	Quarterly	Supports environmental financing criteria
Integrity OPEX versus approved plan	Tracks funding adequacy	Quarterly	Prevents deferred-maintenance risk

10 Host communities and security as integrity barriers

In Nigeria, community engagement is not a public-relations add-on. It is an integrity barrier. A technically sound pipeline that lacks host-community legitimacy remains exposed to illegal tapping, sabotage, access denial and slow emergency response. Recent reporting links improved surveillance and community-oriented security interventions with improved pipeline availability, but the evidence also underscores the need for transparent, independently verifiable performance data [24–26, 35].

The future AIM model for Nigeria should integrate:

- community surveillance contracts;
- transparent grievance channels;
- youth employment in ROW monitoring;
- emergency notification systems;
- local contractor participation;
- benefit-sharing mechanisms;
- anti-vandalism education;
- joint security operation centres;
- clear compensation and remediation protocols.

This approach transforms the right-of-way from a contested corridor into a jointly protected economic asset.

11 Resilience by design: climate, flooding and energy transition

Pipeline design in Nigeria must anticipate climate stress. Flooding, erosion, river migration, heat stress, coastal intrusion and extreme rainfall can undermine shallow-buried pipelines, expose river crossings and damage access roads. Climate-adaptation evidence supports integrating hazard screening, resilience options, lifecycle cost, residual risk and adaptation finance into project preparation rather than treating resilience as a late retrofit [27–30].

- hydrological studies for river crossings;

- erosion and scour modelling;
- deeper burial in high-risk locations;
- HDD or micro-tunnelling for sensitive crossings;
- strain-based design where ground movement is likely;
- remote block valves for isolation;
- redundant communications;
- renewable or hybrid backup power for remote stations;
- methane leak detection and repair systems;
- decommissioning provisions.

This is particularly relevant because Nigeria's gas infrastructure supports power generation, industrial energy and domestic-transition strategies. Pipeline resilience therefore supports national energy security, but the paper does not assume that gas infrastructure is automatically sustainable; methane leakage, flaring, lock-in, transition and decommissioning risks must be measured and managed [22–26].

12 Implementation roadmap for Nigerian operators

Table 7. Five-year AIM and design implementation roadmap.

Phase	Timeframe	Priority Actions	Expected Outcome
Phase 1: Baseline Integrity Recovery	0–12 months	Asset register clean-up, threat register, regulatory gap analysis, CP survey, ROW risk mapping	Known asset condition and risk baseline
Phase 2: Risk-Based Prioritisation	12–24 months	RBI model, ILI campaign, high-risk anomaly repair, leak detection validation	Reduced unknown risk and improved availability
Phase 3: Digital Integration	24–36 months	GIS, SCADA integration, inspection database, dashboard, drone surveillance	Real-time integrity intelligence
Phase 4: Bankability Assurance	36–48 months	Independent technical audit, lender reporting, insurance engineering review, ESG metrics	Improved access to long-term capital
Phase 5: Life Extension and Resilience	48–60 months	Fitness-for-service, climate resilience upgrades, decommissioning fund alignment	Extended asset life and reduced liability

13 Strategic recommendations

13.1 For pipeline operators

Operators should treat AIM as an executive-level value-protection system. Integrity budgets should not be the first casualty of cash constraints. Deferred maintenance is not savings; it is risk transferred into the future with uncertainty and potentially nonlinear consequences [9].

13.2 For regulators

Regulators should continue strengthening inspection, data reporting, risk-based oversight and conformity assessment. NUPRC's existing emphasis on facility integrity, asset reliability and risk-

based inspection provides a foundation for this evolution [5]. Regulatory reporting should be proportionate to risk but sufficiently standardised to support comparison and independent assurance.

13.3 For financiers

Lenders and investors should require AIM documentation as part of technical due diligence. Loan agreements should include integrity KPIs, inspection milestones, emergency-response requirements and reporting covenants. Where sustainability-linked finance is used, target calibration, verification and consequences for missed targets should be explicit [31, 32].

13.4 For government

Government should support a national pipeline integrity data framework, integrate pipeline protection with host community development and incentivise operators that demonstrate measurable integrity performance.

13.5 For the Pipeline Professional Association of Nigeria

The Association can lead by developing Nigerian AIM competency frameworks, certification programmes, case-study repositories and technical forums linking engineering practice with infrastructure finance.

14 Conclusion

The future of Nigerian pipeline infrastructure will not be unlocked by capital alone. It will be unlocked by credible, measurable and governed integrity. Capital follows confidence, and confidence follows evidence. The evidence financiers need is not rhetorical; it is technical: sound design, verified construction, controlled corrosion, monitored pressure, inspected anomalies, protected rights-of-way, trained people, responsive communities and transparent governance [1, 4, 9, 30–33].

Asset Integrity Management and Design should therefore be positioned as a national infrastructure-financing strategy, while recognising that AIM cannot eliminate macroeconomic, regulatory or political risk. When integrity is designed into pipelines, Nigeria gains safer communities, cleaner environments, more reliable throughput, stronger energy security, more attractive infrastructure projects and a clearer path to resilient economic growth [22, 27, 30].

In the language of this conference: financing the future begins by designing assets that deserve the future.

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