Comprehensive Digital Twin Architecture for Predictive Maintenance of Texas Pipelines

1. Introduction: The Imperative for Digital Transformation in Texas Pipeline Infrastructure

The vast and intricate network of energy pipelines crisscrossing the state of Texas represents one of the most complex industrial asset systems in the world. As the operational backbone of the North American energy sector, this infrastructure is subject to a unique convergence of rigorous federal oversight, specific state-level regulation by the Railroad Commission of Texas (RRC), and demanding physical operating conditions ranging from the corrosive humidity of the Gulf Coast to the abrasive, shifting soils of the Permian Basin. The traditional approach to integrity management—often characterized by static document retention, calendar-based maintenance schedules, and reactive repairs—is increasingly insufficient to meet the dual demands of safety assurance and operational efficiency. In this context, the development of a "Digital Twin" moves beyond buzzword status to become a critical engineering necessity.

A Digital Twin for pipeline integrity is not merely a 3D visualization or a database of scanned documents. It is a dynamic, physics-based probabilistic model that fuses real-time operational data with static engineering parameters to predict the future state of the asset. For a Texas operator, this means constructing a system that can ingest T-4 permit data to establish the legal baseline, map it against API 5L material properties to define the physical limits, and apply degradation algorithms derived from ASME B31G and NACE standards to forecast failure probabilities. This report outlines the comprehensive architectural and engineering requirements for building such a system, specifically tailored to the regulatory and physical realities of the Texas energy landscape.

The transition to predictive maintenance relies on the synthesis of disparate data streams. Regulatory data from the RRC provides the geospatial and legal "skeleton" of the pipeline. In-line inspection (ILI) data provides the "snapshot" of current condition. SCADA data provides the "pulse" of operational stress. The engineering standards—ASME B31G, API 570, API 5L, NACE SP0169, and NACE MR0175—provide the "brain," or the logic gates and algorithms that interpret this data. By encoding these standards into the Digital Twin, operators can move from subjective decision-making to algorithmic risk assessment, ensuring that every meter of pipe is evaluated against the most rigorous physics-based criteria available.

2. The Regulatory Data Foundation: Integrating

Railroad Commission of Texas (RRC) Datasets

The genesis of any compliant Digital Twin for Texas pipelines lies in the accurate ingestion and mapping of regulatory data. The Railroad Commission of Texas (RRC) maintains the authoritative record of pipeline existence, ownership, and status. A Digital Twin that is not synchronized with these records risks creating a "shadow asset" that exists in engineering reality but drifts from regulatory truth, leading to compliance violations and administrative penalties.

2.1 The Digital Skeleton: T-4 Permit Data Architecture

The T-4 Permit is the fundamental license to operate a pipeline in Texas. It is not a static document but a dynamic dataset that defines the geospatial and operational boundaries of the asset. For the Digital Twin, the T-4 database acts as the primary key registry, linking internal asset IDs to state-recognized system identifiers.

2.1.1 T-4 Data Schema and Ingestion Logic

The RRC requires operators to submit digital projection data, typically in shapefile format, which adheres to a strict data dictionary. The Digital Twin must be designed to ingest these fields directly, treating them as immutable "truth" for regulatory reporting while allowing for internal "engineering" overrides where field surveys differ from permit records.

Essential T-4 Attribute Fields for Digital Twin Integration:

TPMS Field	Data Type	Description	Digital Twin Implementation Logic
T4PERMIT	Text (5)	The 5-digit RRC assigned permit number.[1]	Serves as the unique foreign key linking the Twin to RRC databases. Validation logic must ensure exactly 5 digits (e.g., "09876") and flag any localized IDs that lack a corresponding state permit.

SYS_NM	Text (40)	System Name assigned by operator.[2]	Used for grouping disparate segments into logical operational units within the Twin's hierarchy.
COMMODITY	Text (3)	Abbreviation for primary commodity (e.g., GAS, OIL).[3]	**Critical Logic Gate:** This field determines which physics modules are activated. "GAS" activates compressible flow models; "OIL" activates hydraulic hammer models; "H2S" flagged commodities trigger NACE MR0175 compliance modules.
DIAMETER	Numeric	Nominal Pipe Size (OD).[1]	The base variable (D) for all hoop stress calculations. The Twin must validate this against API 5L standard sizes to prevent data entry errors (e.g., 6.625" vs 6").
WALL_THICK	Numeric	Nominal Wall Thickness.	The denominator in stress calculations. The Twin uses this for "Nominal" calculations but overrides it with ILI data for "Actual"

			assessments.
T4_AMD	Text (2)	Amendment Code (e.g., NP, TM).[3]	**Event Trigger:** A "TM" (Transfer Merge) code triggers a lineage consolidation protocol, merging historical data from acquired assets into the current Twin.[4]

The ingestion logic must be robust enough to handle the "T-4 Amendment Codes." For instance, when a "TM" (Transfer Merge) code is encountered in the permit update feed, the Digital Twin must initiate a specific workflow: identifying the previous operator's T-4 number, retrieving historical leak and inspection data associated with that ID, and re-indexing it under the new permit number to ensure continuity of the integrity history. This prevents the "data amnesia" that often occurs during asset acquisitions.[4]

2.1.2 Geospatial Synchronization (TPMS vs. ILI)

The Texas Pipeline Mapping System (TPMS) relies on submitted shapefiles which often have a lower positional accuracy (± 50 feet or more) compared to modern Inertial Mapping Unit (IMU) data from Smart Pigs (sub-meter accuracy). The Digital Twin must maintain two geospatial layers: the "Regulatory Centerline" (matched to TPMS for reporting) and the "Engineering Centerline" (matched to IMU for maintenance).

An automated script should run periodically to calculate the deviation between these two centerlines. If the deviation exceeds the RRC's tolerance threshold (typically 500 feet for Class 1, tighter for Class 3/4), the Twin should auto-generate a "Location Correction" filing packet. This proactive approach ensures that the operator's regulatory filings evolve in lockstep with their improved knowledge of the asset's location.[5]

2.2 Leveraging Historical Failure Data: The PS-95 Dataset

Predictive maintenance models require training data—specifically, labelled instances of failure. The RRC's PS-95 "Semi-Annual Leak Report" is a rich repository of failure taxonomy that is specific to the Texas environment. By aligning the Digital Twin's internal incident logging with the PS-95 schema, operators can benchmark their performance against the state-wide aggregate risk.

2.2.1 PS-95 Taxonomy and Predictive Features

The PS-95 report categorizes leaks into specific "Cause Codes." The Digital Twin should not only use these codes for outputting reports but also as input features for its risk models.

RRC PS-95 Cause Codes as Predictive Features:

Cause Group	Code	Description	Predictive Implication for Digital Twin
Corrosion	11	Internal/External Corrosion.[7]	**Validation Signal:** Every internal leak coded "11" should be cross-referenced with the last B31G run. If B31G predicted safety, the model calibration factor (F) must be adjusted.
Excavation	21	Operator/Contractor Digs.	**Geospatial Correlation:** These incidents should be correlated with "One-Call" ticket density. High ticket volume + Code 21 history = High Probability of Failure (POF) zone.
Natural Forces	33	Ground Movement/Subsidence.	**Soil Data Integration:** In areas like the Gulf Coast (subsidence) or North Texas (expansive clay), Code 33 history

			triggers the activation of strain-based design checks in the Twin.[7]
Materials	55	Weld Failure (Steel).	**Vintage Factor:** Correlates with construction year and welding method (e.g., pre-1970 ERW). High incidence suggests systemic vintage risks.

The Digital Twin's reporting module must be capable of serializing internal leak data into the EDI format specified by the RRC (Record Types 1, 2, and 3), using the correct delimiters (right curly bracket }) to ensure automated acceptance of the PS-95 filing.[7]

2.3 Third-Party Risk Integration: Online Research Queries

One of the highest risks to Texas pipelines is third-party damage from the state's intense drilling activity. A static map is insufficient to monitor this dynamic threat. The Digital Twin should utilize the RRC's "Online Research Query" tools to scrape or query "W-1" (Drilling Permit) filings.[8]

Logic for Drilling Encroachment Alerts:

1. **Ingest:** Daily query of new W-1 permits from the RRC database.
2. **Buffer:** Create a geospatial buffer (e.g., 1000 feet) around the Engineering Centerline.
3. **Intersect:** Identify any new W-1 surface locations or bottom-hole paths that intersect the buffer.
4. **Alert:** Trigger a "Proximity Alert" to the encroachments team to verify if a crossing agreement is in place.
5. **Risk Update:** Temporarily elevate the "Third Party Damage" risk factor for that segment in the overall risk matrix until drilling is complete.

This capability transforms the Twin from a passive repository into an active sentinel, detecting threats before a rig even mobilizes to location.

3. The Physical Asset Model: API 5L Material

Properties

To predict how a pipeline will fail, the Digital Twin must first understand what the pipeline is made of. API Specification 5L (Line Pipe) provides the metallurgical DNA of the asset. In a predictive model, "steel" is not a generic material; it is a specific set of probabilistic strength and toughness distributions defined by its Grade and Product Specification Level (PSL).

3.1 Grade-Specific Constants for Engineering Physics

The Digital Twin must utilize exact material properties rather than conservative generic assumptions whenever possible. For modern pipelines, these properties are well-defined by the Grade (e.g., X52, X70).

Key Material Parameters for X-Grade Steels:

API 5L Grade	PSL	Min Yield (SMYS) [psi]	Min Tensile (SMTS) [psi]	Yield/Tensile Ratio	Application Context
Grade B	PSL 1/2	35,500	60,200	0.93 Max	Common in older, low-pressure distribution systems.
X42	PSL 2	42,100	60,200	0.93 Max	Standard for intermediate transmission lines.[9]
X52	PSL 2	52,200	66,700	0.93 Max	Widely used legacy transmission grade.[9]
X60	PSL 2	60,200	75,400	0.93 Max	High-pressure transmissio

					n.
X65	PSL 2	65,300	77,600	0.93 Max	Modern standard for large diameter gas lines.[11]
X70	PSL 2	70,300	82,700	0.93 Max	High-strength, allows thinner wall but requires strict weld control.[9]

Digital Twin Logic for "Unknown" Materials:

For older Texas pipelines where Mill Test Reports (MTRs) are lost, the Twin must default to the conservative assumptions of 49 CFR 192.108 / API 5L.

- *Algorithm:* IF Grade = Unknown AND Year < 1952 THEN Yield = 24,000 psi.
- *Algorithm:* IF Grade = Unknown AND Year >= 1952 THEN Yield = 30,000 psi (assuming verifyable spec).
  This logic ensures that the Twin never overestimates the strength of an unverified asset, maintaining a safety margin in all MAOP calculations.

3.2 Probabilistic Modeling of Wall Thickness

API 5L allows for manufacturing tolerances in wall thickness. A deterministic model assumes the wall is exactly 0.500". A predictive Digital Twin knows it varies.

Tolerance Logic [12]:

- For pipe $t \geq 0.157$ inches, the tolerance is typically $+0.150t / -0.125t$.
- *Monte Carlo Input:* When running burst pressure simulations, the wall thickness t should not be a single scalar but a **Normal Distribution** with a mean of the nominal thickness and a standard deviation derived from the API 5L tolerance range.
- *Impact:* This captures the "tail risk" where a corrosion defect coincides with a spot of pipe that was manufactured on the thin side of the tolerance, significantly reducing the actual burst pressure compared to the nominal calculation.

3.3 Fracture Mechanics and Toughness (Annex G/H)

Predicting rupture versus leak requires knowledge of the steel's toughness—its ability to resist crack propagation.

- **Charpy V-Notch (CVN):** For PSL 2 pipe, CVN testing is mandatory. The Twin should store the specific CVN energy (Joules) and shear area (%) for each heat of steel.[9]
- **Ductile-to-Brittle Transition:** The Twin must monitor the operating temperature against the steel's transition temperature. In Texas, extreme winter events (like Uri in 2021) can drop pipe wall temperatures significantly. If the temperature drops below the ductile-to-brittle transition point of an older X-grade steel, the risk of catastrophic brittle fracture increases. The Twin should ingest real-time ambient/ground temperature data and flag segments operating in their "brittle window" during cold snaps.

4. External Corrosion Control: NACE SP0169 and Cathodic Protection

External corrosion is the primary threat to buried steel in Texas soils. The defense is a dual system of coating and Cathodic Protection (CP). The Digital Twin must virtualize the CP system to detect failures in this shield before metal loss occurs.

4.1 The Physics of Protection: NACE SP0169 Criteria

NACE SP0169 defines the voltage thresholds that constitute "protection." The Digital Twin must evaluate CP survey data against these logic gates to classify segments as "Protected" or "At Risk."

Criteria Logic for Digital Twin Algorithms [13]:

1. **Criterion 1: -850 mV "ON" (Potential with IR Drop):**
   - *Input:* Pipe-to-Soil (P/S) potential with rectifier current flowing.
   - *Logic:* P_on <= -0.850 V.
   - *Limitation:* This reading includes "IR Drop" error (voltage drop through the soil/coating). It is often overly optimistic.
2. **Criterion 2: -850 mV "OFF" (Polarized Potential):**
   - *Input:* "Instant Off" potential measured immediately after interrupting current.
   - *Logic:* P_off <= -0.850 V.
   - *Significance:* This is the most accurate representation of the pipe's polarization. The Digital Twin should prioritize P_off data where available. A reading of -0.840 V is a "Fail," even if the "ON" reading was -1.200 V.
3. **Criterion 3: 100 mV Polarization Shift:**
   - *Input:* P_off and P_native (depolarized potential).
   - *Logic:* abs(P_off - P_native) >= 0.100 V.
   - *Context:* Useful in old, bare pipelines where achieving -0.850 V is impossible due to high current requirements.

4.2 Handling AC Interference in Texas Corridors

In Texas, pipelines often share Right-of-Way (ROW) with high-voltage HVAC transmission lines. This creates a risk of AC corrosion, which can destroy a pipe even if the DC CP levels are perfect.

AC Interference Module Logic [14]:

- **Induction Modeling:** The Twin should ingest the spatial path of HVAC lines. Where parallel runs exceed 1 mile and separation is < 1000 feet, an "AC Risk Zone" is established.
- **Current Density:** The critical parameter is AC current density (A/m^2).
  - *Safe:* $< 30A/m^2$.
  - *Risk:* $30 - 100A/m^2$.
  - *Severe:* $> 100A/m^2$.
- **Alerting:** If AC coupon readings exceed 30 A/m^2 , the Twin must trigger an alert for "AC Mitigation Required," regardless of the DC potentials.

4.3 Soil Corrosivity Mapping

Texas soil varies from high-resistivity sand to low-resistivity, high-chloride coastal clay. The Digital Twin should integrate USDA Soil Survey (SSURGO) data layers.

- **Resistivity ($ \rho $):** Low resistivity (< 1000 ohm-cm) implies high corrosion rates.
- **Predictive Weighting:** In the absence of ILI data, the "Prior" probability of corrosion in the Bayesian risk model should be weighted by the local soil resistivity. Risk_Corrosion ~ 1 / Resistivity.

5. Internal Corrosion and Sour Service: NACE MR0175

Internal corrosion is a function of the commodity transported. In Texas, the prevalence of "Sour Gas" (H2S-rich) necessitates strict adherence to NACE MR0175 / ISO 15156. The Digital Twin must act as a continuous metallurgical auditor, ensuring the pipe material is compatible with the ever-changing stream chemistry.

5.1 Defining the "Sour" Threshold

NACE MR0175 defines the boundary between "Sweet" and "Sour" service. This is not a static designation; it depends on operational pressure.

The Sour Algorithm [15]:

- **Input:** System Total Pressure (P_{sys}), H2S concentration in mole fraction (Y_{H2S}).
- **Calculation:** Partial Pressure $pH_2S = P_{sys} \times Y_{H2S}$.
- **Logic:**
  - IF pH2S < 0.05 psia (0.3 kPa) THEN Service = Sweet (NACE compliance optional).
  - IF pH2S >= 0.05 psia (0.3 kPa) THEN Service = Sour (NACE compliance mandatory).

Operational Implication: A pipeline transporting gas with 10 ppm H2S might be "Sweet" at 500 psi but become "Sour" if the pressure is ramped up to 1000 psi. The Digital Twin must monitor real-time SCADA pressure and gas chromatograph data to detect these "Sour Excursions" dynamically.

5.2 The Domain Diagram: Mapping Severity Regions

Once in sour service, the severity is mapped on the "Domain Diagram" (Figure 1 of NACE MR0175 Part 2), plotting pH vs. H2S Partial Pressure.

Region Logic [15]:

- **Region 0:** Below 0.05 psi pH_2S .
- **Region 1 (Mild):** Low pH_2S (< 0.1 psi) and high pH.
- **Region 2 (Intermediate):** Moderate conditions.
- **Region 3 (Severe):** High pH_2S (> 15 psi) or low pH.

The Digital Twin should visualize the pipeline's operating point on this diagram in real-time. If the operating point drifts from Region 1 into Region 3 (e.g., due to a water upset lowering pH), the Twin triggers a "Metallurgical Risk Alert."

5.3 Material Compatibility Checks

For segments operating in Region 2 or 3, the Twin must verify material properties against NACE limits.

- **Hardness Limit:** For Carbon Steel, hardness must be ≤ 22 **HRC** (Rockwell C).[17]
- **Nickel Content:** Must be $< 1\%$ to prevent sulfide stress cracking (SSC).
- **Twin Validation:** The Twin queries the "Material Properties" table for the active segment. IF Region >= 2 AND (Hardness > 22 OR Nickel > 1%) THEN Risk = Critical. This identifies "legacy" pipe segments that may have been safe in sweet service but are now ticking time bombs in sour conditions.

6. Defect Assessment Engines: ASME B31G and

RSTRENG

When corrosion is detected, the Digital Twin must determine: "Will this pipe burst?" This is the domain of ASME B31G and RSTRENG. These are not just guidelines; they are the mathematical kernels of the Twin's integrity engine.

6.1 The Logic of Conservatism: Level 1 Assessment

The Twin first applies the **Original B31G** (Level 1) check. This is a rapid screening tool.

Formula [19]:

$$P' = 1.1P \left[\frac{1 - \frac{2}{3}\left(\frac{d}{t}\right)}{1 - \frac{2}{3}\left(\frac{d}{t}\right)\frac{1}{M}} \right]$$

where $M = \sqrt{1 + 0.8\left(\frac{L^2}{Dt}\right)}$.

- **Assumption:** It assumes the defect is a smooth parabola ($Area = 2/3 \cdot d \cdot L$).
- **Result:** It is overly conservative. Many defects that "fail" B31G are actually safe.
- **Twin Workflow:** If P' >= MAOP, the defect is marked "Safe/Monitor." If P' < MAOP, the Twin automatically escalates to Level 2.

6.2 The Logic of Precision: Modified B31G (0.85dL)

Level 2 reduces conservatism by acknowledging that defects are rarely perfect parabolas and modern steel is tougher than 1970s assumptions.

Modifications [20]:

1. **Flow Stress:** Changed from $1.1 \cdot SMYS$ to $SMYS + 10,000$ psi. This gives "credit" for the strain hardening of modern steel.
2. **Area Factor:** Changed from 0.67 ($2/3$) to 0.85. This assumes a more rectangular shape, which is paradoxically *more* conservative in shape but balanced by the higher flow stress and better Folias factor.
3. **Folias Factor:** Uses the expanded 3-term equation for better accuracy on long defects.

Twin Workflow: If P_mod >= MAOP, mark "Safe/Monitor." If P_mod < MAOP, escalate to Level 3.

6.3 The "River Bottom" Algorithm: RSTRENG (Level 3)

This is the most computationally intensive and accurate method. It requires the Twin to process the raw ILI depth array (the "River Bottom" profile).

The RSTRENG Loop [20]: The algorithm does not just look at the total length L. It iteratively examines every possible sub-defect within the corrosion cluster.

- **Input:** Array of depths $d_1, d_2, ...d_n$ at spacing s.
- **Loop:**

  For $i = 1$ to n:

  For $j = i + 1$ to n:

  1. Calculate Sub-Length $L_{sub} = (j - i) \times s$.

  2. Calculate Average Depth d_{avg} over this sub-length.

  3. Calculate P_{burst} for this specific sub-cluster.
- **Minimization:** The Digital Twin identifies the *minimum* burst pressure found in any iteration. This identifies the "weakest link" within a long, complex corrosion patch.

Value: RSTRENG often "saves" pipe that B31G would condemn, saving the operator millions in unnecessary digs. The Digital Twin automates this sophisticated analysis that would be impossible to do manually for thousands of anomalies.[20]

7. Lifecycle Management and Repair Logic: API 570

Identifying a defect is half the battle; deciding *when* to fix it is the other. API 570 provides the logic for inspection intervals and repair decisions.

7.1 Dynamic Inspection Scheduling (RBI)

The Digital Twin replaces static "5-year" intervals with dynamic dates based on corrosion rates.

Remaining Life (RL) Algorithm [23]:

$$RL = \frac{t_{actual} - t_{min}}{\max(CR_{ShortTerm}, CR_{LongTerm})}$$

- **Logic:** The Twin calculates the Corrosion Rate (CR) using the thickness delta between the current ILI and the previous one. It conservatively uses the higher of the Short-Term or Long-Term rate.
- **Next Inspection Date:**

$$Date_{next} = Date_{current} + \min\left(\frac{RL}{2}, \text{Class Limit}\right)$$

- *Rule:* You must inspect before half the remaining life is gone. If $RL = 10$ years, you must inspect in 5 years.
- *Class Limit:* API 570 caps the interval (e.g., 5 years for Class 1, 10 years for Class 2) regardless of how thick the pipe is.[25]

7.2 The Repair Decision Tree

When a defect is flagged as critical ($RL < \text{Lead Time}$), the Twin uses API 570 / ASME PCC-2 logic to recommend a repair type.

Repair Logic Engine [26]:

1. **Is it a Crack?**
   - YES $\rightarrow$ **Cut Out / Replace Cylinder.** (Sleeves are risky for cracks unless strictly designed for containment).
2. **Is it General Thinning?**
   - YES $\rightarrow$ Check Pressure/Strength.
3. **Can we Weld?**
   - IF SMYS < 40,000 psi AND Defect is Small $\rightarrow$ **Fillet Welded Patch** allowed.
   - IF SMYS >= 40,000 psi (High Strength) $\rightarrow$ Patches prohibited. Use **Full Encirclement Sleeve** (Type B).
4. **Is the Line Live?**
   - YES $\rightarrow$ **Composite Wrap** (ASME PCC-2 Art 4.1) or **Bolted Clamp**.
   - NO $\rightarrow$ **Weld Repair** or **Replace Spool**.

This logic ensures that the field crew is dispatched with the *correct* repair plan (and materials) before they even dig the hole.

8. Predictive Analytics: From Digital Twin to Crystal Ball

The ultimate value of the Digital Twin lies in prediction—forecasting the state of the asset 5, 10, or 20 years into the future.

8.1 Monte Carlo Simulation of Failure Probability

Deterministic models (single inputs) define "Safe" or "Fail." Probabilistic models define "Risk."

The Monte Carlo Module:

Instead of calculating RSTRENG once, the Twin runs it 10,000 times, varying the inputs based on their uncertainty distributions:

- **Depth (d):** Normal Distribution (Mean = ILI report value, Std Dev = Tool Error $\pm 10\%$).
- **Wall (t):** Normal Distribution (Mean = Nominal, Std Dev = API 5L Tolerance).
- **Strength (S):** Lognormal Distribution (Mean = SMYS $\times$ 1.1).

Output: The result is not a single pressure, but a Probability of Failure (POF) curve.

- *Insight:* "There is a 0.01% chance of failure this year, rising to 5% in year 5." This allows the operator to set a risk tolerance (e.g., maintain POF < 10^{-4}) and schedule maintenance exactly when that threshold is crossed, optimizing OPEX.[28]

8.2 Corrosion Growth Rate (CGR) Optimization

The Twin improves itself over time. By comparing sequential ILI runs (e.g., 2018 vs. 2023), the Twin calculates the *actual* CGR for every joint of pipe.

- **Spatial Clustering:** It identifies "Hot Spots" where CGR is statistically higher (e.g., low points in the line where water collects).
- **Feedback Loop:** These localized CGRs are fed back into the Remaining Life model, replacing generic default rates. The Twin becomes "smarter" with every inspection.

9. Conclusion

The construction of a pipeline Digital Twin for the Texas regulatory environment is a rigorous exercise in data synthesis and engineering logic. It requires the seamless integration of the RRC's legal frameworks (T-4, PS-95) with the uncompromising physical laws codified in API, ASME, and NACE standards.

By building this system, an operator transforms their asset management from a reactive posture—chasing leaks and reacting to regulatory notices—to a proactive, predictive stance. The Digital Twin does not just store data; it simulates the future. It calculates the stress in a corroded pit before it fails; it predicts the souring of a gas stream before the steel cracks; and it schedules the repair truck exactly when needed—not too soon (wasting money) and not too late (risking safety). In the demanding energy landscape of Texas, this digital infrastructure is as critical as the steel infrastructure it protects.

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