



Classification of Operating Envelope Exceedance Modes and Failure Signatures in Reciprocating and Scroll Compressors

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Abstract

Compressor manufacturers publish an operating envelope on the plane of evaporating and condensing temperatures, and their selection software displays the specific envelope linked to each compressor model. Compressors keep failing at sites where this envelope was available to the system designer and to the operator, and this review examines why the operating conditions of real-world systems exceed the limits of the envelope and why compressors still fail when the working point stays inside it. The material combines published descriptions of envelope boundaries with six failure cases drawn from first-hand engineering practice in commercial refrigeration and cooling systems operating on halocarbon refrigerants: direct site attendance, direct inspection of failed machines, and recommendations issued to plant owners. The cases are classified along two axes. The first axis identifies the mechanism that moved the operating point: modification of the plant by the owner, an assembly or service error, gradual degradation in service, or a selection mismatch between the evaporator and the compressor. The second axis indicates the relationship between the final operating point and the envelope: crossing an explicit boundary, violating an implicit assumption on which the envelope rests, or continuing operation within the published limits. Each case represents one distinct mode, so the six cases yield six modes. Each mode is paired with the physical signature that post-failure inspection of the compressor reveals, from carbonized oil on the cylinder wall to a discharge reed fractured at its root. Two of the six modes result in failure without the working point leaving the limits defined by the operating envelope, which supports the central claim of the review: the envelope is a necessary but insufficient condition for safe operation. The resulting matrix leads the field engineer from the post-failure inspection finding back to the system-level cause.

Keywords: Reciprocating Compressor, Operating Envelope, Application Limits, Failure Signature, Discharge Temperature, Suction Superheat, Reed Valve, Commercial Refrigeration.

INTRODUCTION

Six years of design and troubleshooting work in commercial and industrial cooling systems produced one recurring observation. Compressors at customer sites were operating outside the manufacturer's published operating envelope and failed as a result. The documentation warned against such an operation, and the warning had no effect on what happened in the machine room or on the working point at which customer installations chose to run their compressor equipment. This observation grew out of first-hand practice: site visits to plants with failed compressors, direct post-failure inspection of the failed machines, root-cause reports written for the owners, and later design work on refrigeration plants where the same envelope had to be respected on paper before any steel was cut. The present review organizes that experience into a classification.

The operating envelope of a positive displacement refrigeration compressor is a closed region on the plane of saturated suction temperature and saturated discharge temperature within which the manufacturer permits continuous operation (Boudreau, 2013). Every edge of the region corresponds to a physical limit of the machine. Fig. 1 shows a generalized envelope of a reciprocating compressor with each boundary named by the limit it represents. The left edge is the minimum evaporating temperature, set by the amount of refrigerant vapor available to cool a suction-gas-cooled motor. The right edge is the maximum evaporating temperature, set by the gas forces on the running gear and by the thickness of the oil film under those forces. The lower edge is the minimum condensing temperature, below which discharge superheat becomes too small, and refrigerant condenses in the cylinder head. The upper edge is the maximum condensing temperature, determined by the

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housing's design pressure and motor load, and the upper-right corner, where both saturation temperatures reach their maximum, marks the motor limit at which motor load peaks. The sloping cut in the upper-left corner is the thermal limit at high pressure ratio, where suction density is low, the heat of compression is at its peak, and the discharge temperature threatens the oil. The sloping cut in the lower-right corner marks the limit of low pressure ratio, where mass flow is high and the reed valves carry their largest stresses. The shaded band along the thermal limit marks the region where the manufacturer permits operation only under a restricted suction superheat or with additional head fan cooling.

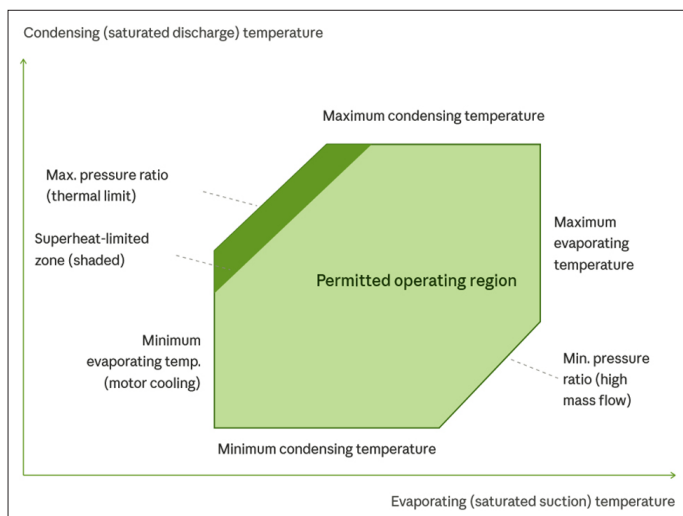


Fig. 1. Generalized operating envelope of a reciprocating compressor with boundaries named by their physical limits

Selection software from compressor manufacturers reproduces this envelope for each model and rejects a duty point that falls outside it. The software answers one question: whether a given pair of saturation temperatures is allowed. It does not answer how a real plant arrives at that operating point, how long it stays there, or which internal part will fail first as a result of that operating point. Engineers who select equipment learn to trust the graphic without learning the physical meaning of each edge, and the system operators and technicians who service plants seldom see the graphic at all.

Published work on faults in vapor compression systems has grown over the last decade, and much of it focuses on detection. Aguilera et al. (2022) reviewed faults reported for fifty-three large-scale heat pumps and found that the compressor, the evaporator, and the source heat exchanger were the components with the most recurrent problems. Experimental campaigns have mapped the response of operating variables to imposed faults such as heat exchanger fouling, refrigerant undercharge and overcharge, and non-condensable gas in the circuit (Catrini & Piacentino, 2025; Zhou et al., 2022). This literature characterizes faults by their symptom in the running plant. The physical trail that the same fault leaves inside the compressor, visible only after the machine has been opened, receives less attention, and within the sources available for this review, no scheme connects the

drift mechanism, the position of the final operating point relative to the envelope, and the signature found when the failed compressor is opened for inspection.

The review pursues three tasks: to state the physical meaning of each envelope boundary without the letter codes that differ from one manufacturer's drawing to another, to classify the routes by which the operating point leaves its design position along two axes, and to pair each route with the failure signature that post-failure physical inspection reveals. The classification is built as a typology, and its practical use is to allow an engineer standing over an open compressor to read the signature and look for the cause in the plant.

MATERIALS AND METHODS

The published component of the review draws on three kinds of sources: trade literature that explains the envelope from the manufacturer's side (Boudreau, 2013) together with public manufacturer documents that state application limits at a reference suction gas temperature, peer-reviewed work on faults in vapor compression systems and their diagnosis (Aguilera et al., 2022; Catrini & Piacentino, 2025; Hu & Yuill, 2023; Zhou et al., 2022), and peer-reviewed work on the internal physics that the envelope encodes, from lubrication (Górny et al., 2022; Tijani et al., 2025) and reed valve dynamics (Yang et al., 2026) to heat exchanger fouling (Inamdar et al., 2023) and two-stage compression (Aksoy & Çerçi, 2026). Sources under confidentiality agreements were excluded.

The practice component consists of six failure cases from first-hand engineering work in commercial and industrial cooling applications operating on halocarbon refrigerants, the fluids known in the trade as Freon, over six years: direct attendance at customer sites with failed compressors, direct inspection of the opened machines, root-cause reports, and follow-up recommendations to the owners. The cases are reconstructed from engineering notes and recollection, and the review therefore reports no statistics, no frequency of any mode, and no causal inference beyond the mechanism visible in each machine. Companies, sites, and equipment models are unnamed. The level of geographic detail kept in the text, such as a chemical plant in the North West Province of South Africa or a compressor rack builder in Europe, is the level at which the cases were recorded, and the text does not refine it. One measured quantity enters the text: in the first case, the suction superheat reading on the running plant, in the presence of the site engineer, was between 25 and 35 °C, against a recommended range of 10 to 20 °C for the installed compressors. The capacities of 100 kW and 140 kW quoted in the sixth case are a worked illustration constructed to explain the mechanism. The compressors in five of the six cases are semi-hermetic reciprocating machines, and the compressor in the third case is a scroll machine. None of the plants operated on ammonia or propane.

Classification proceeds along two axes. The first axis records the mechanism that displaced the operating point and admits four values: modification of the plant by the owner, an assembly or service error at commissioning or start-up, gradual degradation in service, and a selection mismatch between components. The second axis records the relationship between the final operating point and the published envelope and admits three values: crossing an explicit boundary, violating an implicit assumption on which the envelope is based, and continuing operation within the published limits. Each case was placed in a cell of this grid on the evidence available for it: site measurements and post-failure inspection where a failed compressor reached the workshop, and the traced mechanism where it did not. The failure signature was then recorded as the physical condition that post-failure inspection finds or that the mechanism predicts: the state of the oil, the condition of the sliding surfaces, the condition of the valve plate, and the condition of the housing.

The envelope shown in Fig. 1 and reused in Fig. 2 is a generalized schematic and does not represent any specific model. Boundaries carry physical names, and the trajectories in Fig. 2 start from a common design point so that the direction of each drift can be compared. The dashed ring for the third mode in Fig. 2 marks a violated assumption and ties no scroll geometry to the reciprocating envelope. No manufacturer drawing, software screen, or brochure page is reproduced.

RESULTS

The six cases fall into six distinct modes of envelope exceedance. Fig. 2 places all six on the generalized envelope of Fig. 1 and numbers them in the order used throughout this section. Four trajectories cross an explicit boundary, one mode violates an implicit assumption while the operating point remains inside the region, and one trajectory moves toward the upper right corner and stays inside the published limits.

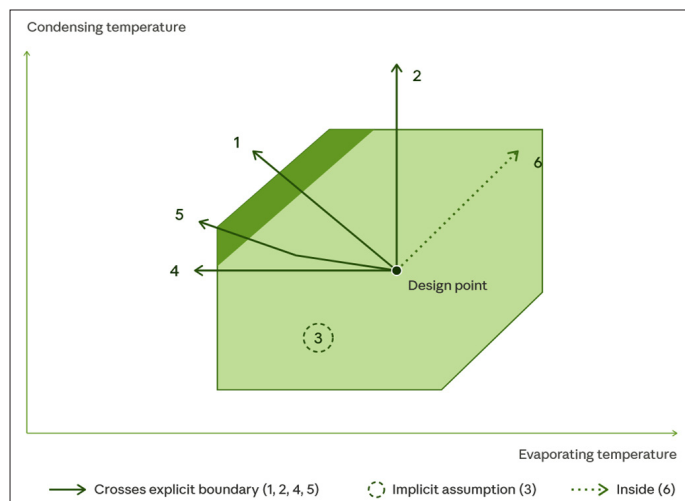


Fig. 2. Trajectories of the operating point for the six exceedance modes on the generalized envelope

The first mode is a modification of the plant by its owner. A chemical plant in the North West Province of South Africa cooled the glycol jacket of an exothermic reactor with a two-stage refrigeration system. A site inspection found that the low-temperature stage had been dismantled and decommissioned, so the remaining compressors compressed the refrigerant from the evaporating pressure to the condensing pressure in a single step. Intercooling disappeared with the second stage, and the pressure ratio across each machine rose to a level the two-stage design had been built to avoid. The plant operated on R507, a halocarbon blend, and the physics matches what Aksoy and Çerçi (2026) describe for a two-stage ammonia plant: single-stage compression at low evaporating pressure raises the discharge temperature, and two-stage compression exists to keep the compressors within a favorable operating range, whatever the working fluid. On the envelope, the trajectory runs far to the left while the condensing temperature, held up by the ambient conditions, stays high, so the operating point crosses the thermal limit in the upper-left corner. The measured suction superheat of 25 to 35 °C, compared with the recommended 10 to 20 °C, confirmed elevated gas temperatures on the running plant. Post-failure inspection of the failed reciprocating compressors revealed carbonized oil on the compression chamber wall and discolored, near-black oil in the main reservoir, whereas fresh oil of the same grade is clear with a pale straw or light yellow color. Several compressors failed in succession at this site.

The second mode is an assembly error that closes the discharge path. A compressor rack builder in Europe installed a check valve in the discharge line of a reciprocating compressor with its flow arrow reversed. At commissioning, the compressor started against a closed line, and pressure accumulated in the cylinder head and housing without relief. Within seconds of start, the cast-iron shell fractured, and the compressor burst. The motor was still intact when the housing failed. On the envelope, this mode follows a vertical trajectory: the evaporating temperature does not change, and the condensing-side pressure climbs through the maximum condensing temperature and far beyond the top of the drawing. The failure signature is unmistakable at the site: a ruptured housing with no thermal damage to the oil, pointing to a blocked discharge path. Valves installed in reverse are a recurring commissioning error in field-built systems, and some modern carbon dioxide compressors now carry an internal relief valve directly on the compressor's metal housing for this reason.

The third mode is a service error that violates an assumption the envelope never states. A supplier of building cooling systems charged liquid R404A into a service port on a scroll compressor. Liquid refrigerant belongs in the receiver or upstream of the evaporator, where it flashes and enters the compressor in the gas state, as the manufacturer and the operating guidelines require. When charged into the

compressor, the liquid washes the lubricating oil off the contact surfaces of the scroll set, and at the next start, the surfaces meet without a film. In envelope terms, the suction superheat at start approaches 0 K, while every boundary of the envelope is drawn on the assumption that the gas entering the compressor is superheated by a recommended amount stipulated by the compressor manufacturer. The operating point, plotted as a pair of saturation temperatures, sits inside the permitted region throughout. Górný et al. (2022) showed in block-on-ring tests that refrigerant dissolved in compressor oil raises the measured wear volume under starved lubrication by 40 to 120% relative to the oil alone, so that the worst mixture produced more than twice the wear of the pure oil, and they observed that starved lubrication is absent from the design assumptions of a compressor and arises as a consequence of how the system is operated. Inspection of several scroll compressors at this site revealed wear marks and scratches from metal-to-metal contact and heat marks on the inner moving parts. Fig. 2 marks this mode with a dashed ring inside the envelope, because it has no trajectory to draw.

The fourth mode is gradual degradation in service through evaporator fouling. A fouled evaporator transfers less heat than its design duty, and its effect on the compressor is the same as that of an undersized evaporator. As the evaporating temperature falls, suction pressure falls with it, the pressure ratio increases, and the operating point moves to the left along a near-horizontal path toward the minimum evaporating temperature. Air-side fouling of finned heat exchangers is a slow and common process, and Inamdar et al. (2023) reviewed its mechanisms and proposed a test protocol because the field lacked one. When the point reaches the left edge, the suction-gas-cooled motor loses its cooling flow, and the discharge temperature has risen with the pressure ratio. Oil temperature follows discharge temperature, viscosity decreases as oil temperature increases, and the oil film between sliding surfaces thins as a direct result of that oil temperature increase. Tijani et al. (2025) trace the same chain in the context of high-temperature heat pumps: working fluid dissolved in the oil lowers the working viscosity, and lower viscosity raises wear under the same load. The post-failure signature of this mode is blackened oil and, after prolonged operation, wear marks and scratches from metal-to-metal contact on the moving surfaces of the reciprocating machine.

The fifth mode is gradual degradation through a slow, unrepaired refrigerant leak. A shrinking charge starves the evaporator; suction pressure falls, suction superheat rises, and mass flow through the compressor drops as the active working fluid is lost. The operating point again drifts left toward the minimum evaporating temperature, and the reduced mass flow removes the cooling that a suction-gas-cooled motor depends on, so the failure path leads to motor overheating. This mode has a second branch that the fourth

one lacks. A leak on the low side of a system operating below atmospheric pressure allows air to enter, and its components accumulate in the condenser as non-condensable gases. Hu and Yuill (2023) observed that non-condensable gas entering the circuit through improper installation or service lowers efficiency, increases load on the compressor, and shortens its life. Ali et al. (2025) quantified the effect on an R134a system: at an air fraction of 3.3%, power consumption increased by 37.1%, the coefficient of performance decreased by 42.8%, and the compressor temperature increased. Condensing pressure climbs with the partial pressure of the air, discharge temperature climbs with condensing pressure, and the operating point acquires an upward component in addition to its leftward one. Fig. 2 shows the trajectory bending toward the upper left. The post-failure signature combines the thermal marks of the fourth mode with evidence of motor overheating.

The sixth mode is a selection mismatch, and it is the mode on which the review's central claim rests. A worked illustration pairs a reciprocating compressor rated at 100 kW of cooling capacity with an evaporator sized for 140 kW at the same conditions. The oversized evaporator has more surface than the cooling load requires and a greater capacity to accept refrigerant flow. The expansion device opens to feed it; mass flow through the compressor rises above the level a matched evaporator would demand, gas velocity through the discharge ports rises with mass flow, and the surplus surface raises suction superheat beyond the setting a matched coil would produce. As the evaporating temperature rises, the condensing temperature increases with the added heat rejection, and the operating point moves toward the upper-right corner of the envelope while remaining within the published limits. The new combination of mass flow, suction gas density, and pressure pulsation changes the dynamic loading of the discharge reeds. Yang et al. (2026) modeled and measured the response of a discharge reed and found that its closure lags the reversal of pressure across the valve, that the lag originates in reed inertia, and that a mismatch between the response time of the reed and the time scale of the pressure change governs reverse flow through the port. Under elevated flow and velocity, the same mismatch drives the reed into flutter, an unstable oscillation fed by reed elasticity, gas force, and pulsating flow. The failure signature is a discharge reed fractured at its root, where it is clamped to the valve plate, with fragments in the cylinder and a piston damaged by them. The literature has long noted that valve stress peaks near the low-pressure-ratio boundary of the envelope (Boudreau, 2013). The sixth mode shows the same stress occurring well within the envelope when the evaporator is mismatched with the compressor.

Table 1 gathers the six modes in a single matrix. Each row records the mode, its values on the mechanism and envelope axes, the trajectory direction on the plane of Fig. 2, and the signature found at post-failure inspection. Row numbers match those in Fig. 2.

Table 1. Matrix of envelope exceedance modes, drift mechanisms, envelope relations, and post-failure signatures

No.	Mode	Drift mechanism	Relation to envelope	Trajectory of operating point	Post-failure signature
1	Low-pressure stage removed from a two-stage plant	Modification by the owner	Explicit boundary: maximum pressure ratio and discharge temperature	Far to the left with condensing temperature held high, beyond the thermal limit	Carbonized oil on the compression chamber wall, near-black oil in the sump
2	Discharge check valve installed in reverse	Assembly error at commissioning	Explicit boundary: maximum condensing and housing pressure	Vertical, within seconds, far beyond the envelope	Cast iron housing rupture with intact motor and clean oil
3	Liquid refrigerant charged into a scroll compressor service port	Service error during first system start	Implicit assumption: suction superheat and oil film at start	None to draw, superheat approaches 0 K, oil washed from surfaces	Wear marks and scratches from metal-to-metal contact on internal moving parts
4	Fouled evaporator	Degradation in service	Explicit boundary: minimum evaporating temperature	Near-horizontal to the left toward the minimum evaporating limit	Blackened oil, reduced viscosity, wear marks and scratches after prolonged operation
5	Slow refrigerant leak with ingress of non-condensable gases	Degradation in service	Explicit boundary: minimum evaporating temperature with rising condensing	Left and upward at once, starved evaporator plus air in the condenser	Blackened oil and motor overheating with elevated discharge temperature
6	Evaporator oversized relative to compressor capacity	Selection mismatch	Inside the envelope: mass flow and valve loading unrepresented	Toward the upper right corner, inside the published limits	Discharge reed fractured at its root, fragments in the cylinder

DISCUSSION

Two of the six modes end inside the published envelope. The third mode violates the superheat assumption on which every boundary of the compressor operating envelope is based, and the sixth mode raises mass flow and valve loading to levels that neither saturation temperature records. The envelope is therefore a necessary but insufficient condition for safe operation. It constrains two variables, saturated suction temperature and saturated discharge temperature, and it holds several others fixed by convention: a stated suction gas temperature or superheat, a lubricated start, a matched evaporator, and an open discharge path. Manufacturer documents make the first of these conventions explicit by printing application limits with a reference suction gas temperature, while leaving the others unstated. A selection engineer who reads the envelope reads the two constrained variables and inherits the conventions without seeing them.

This distinction explains the gap between what selection software shows and what happens in physical real-world systems during operation. The software confirms that a pair of saturation temperatures is permitted, and it has no knowledge of whether the plant will reach that pair through a stage the owner has removed, a coil that fouls over a season, or a charge that leaks over a year. The two axes of the classification answer the questions the software leaves open: the mechanism axis tells the engineer where in the plant to look, and the signature column tells the engineer, standing over an opened compressor, which mechanism to suspect. A

ruptured housing with clean oil points to a blocked discharge path. Carbonized oil on the cylinder wall indicates sustained high discharge temperatures. Wear marks and scratches in a scroll set with no thermal discoloration of the oil points to a lubrication loss at the start. A reed broken at its root, in a machine whose operating point never left the envelope, points to a flow mismatch upstream.

The modes differ in the time they take. The first mode lasts for as long as the owner runs the plant in its modified form, the second mode ends within seconds of the first start, the third does its damage during the first starts after charging, the fourth and fifth unfold over months of drift, and the sixth is a steady state that persists for the life of the reed. Each time scale calls for a different protection. Against the abrupt mode, the protection is mechanical, including an internal relief valve on the compressor housing and a commissioning check of each valve's orientation before the first start. Against the slow drifts, the protection lies in monitoring, since a discharge gas temperature sensor and motor winding sensors register the drift long before the oil blackens. Against the steady-state mode, the protection belongs to the design stage, in a check of evaporator capacity against compressor capacity at the actual operating conditions, since no sensor on the compressor will report a mismatch that the envelope permits.

The classification agrees with the published description of the envelope and extends it in one direction. Boudreau (2013) explains each boundary and the consequences of

crossing it from the manufacturer's side, and the third section of this review reaches the same conclusions from the post-failure inspection side. The fault literature characterizes faults by the symptoms they produce in a running plant: Catrini and Piacentino (2025) built a symptom matrix that maps condenser fouling, undercharge, and overcharge onto discharge pressure, subcooling, and fan power; Zhou et al. (2022) measured drops in coefficient of performance of up to 47.6% from outdoor unit fouling alone, and Aguilera et al. (2022) found that faults in the compressor and the evaporator recur more often than faults elsewhere in large heat pumps. Table 1 operates on the opened compressor, where the running data are gone, and only the physical trail remains. It is offered as the second half of a diagnostic that begins with those symptom matrices. Within the sources available for this review, the combination of the drift mechanism, envelope relation, and post-failure signature in a single scheme was absent from earlier work, and the classification is presented on that basis without a claim of priority.

Several consequences follow for the selection of compressors and evaporators and for the operation of the plants they serve. Firstly, an evaporator should be checked against the compressor under the plant's operating conditions, because a coil with surplus capacity adds load to the discharge valves in addition to providing cooling margin. Secondly, a two-stage plant that has lost a stage has changed its compressor duty and should be re-selected as a single-stage plant, with compressors of higher refrigeration capacity installed to compensate for the change, before it runs again. Thirdly, the suction superheat reading on the running plant is a proxy for the discharge temperature, and a reading above the recommended range indicates that the point is approaching the thermal limit, even when the saturation temperatures remain within the envelope. Fourthly, liquid refrigerant should enter the circuit only where it can flash before reaching the compressor. Fifthly, a commissioning checklist should record the flow direction of every check valve in the discharge line and confirm that every shut-off valve in the working fluid path is open before power is applied.

The review has limits that follow from its material. The six cases are a typology built from engineering notes and recollection of first-hand site work, and the review makes no statement about how often any mode occurs or which mode dominates in a given sector. The modes are drawn from one practitioner's track in one segment of the industry: semi-hermetic reciprocating machines with one scroll machine, all operating on halocarbon refrigerants. Screw compressors, with their own envelope geometry and oil management, are absent. The capacities in the sixth mode are a constructed illustration. The two-axis grid has twelve cells, and the six cases fill five of them, so the classification remains open to modes that were not encountered. Future work could test the matrix against a body of failure reports held by a manufacturer or an insurer, count the frequency of

each signature, and extend the axes to screw and centrifugal machines.

CONCLUSION

Exceedance of the compressor operating envelope is a family of distinct modes and can be classified along two axes: the mechanism that moves the operating point and the relation of the final point to the published limits. Six failure cases from first-hand practice in commercial refrigeration and cooling systems operating on halocarbon refrigerants fill five cells of that grid. An owner who removes a compression stage drives the point across the thermal limit. An installer who reverses a check valve drives the pressure through the top of the envelope in seconds. Fouling and leakage drag the point toward the minimum evaporating temperature over months. A technician who charges liquid into a scroll compressor, and a designer who pairs a compressor with an oversized evaporator, leave the point inside the envelope and break the machine all the same.

Each mode leaves a signature that post-failure inspection reveals: carbonized oil on the cylinder wall for sustained high discharge temperature, a ruptured cast iron housing with intact oil for a blocked discharge path, wear marks and scratches in a scroll set without thermal marks for a lubrication loss at start, and a discharge reed broken at its root for a flow mismatch that the two saturation temperatures never showed. The signature is the entry point for the engineer's classification in the field, because the running data is gone by the time the machine is opened.

The envelope is a necessary condition of safe operation and an insufficient one. Two of the six modes produce failure at operating points the manufacturer permits, because the envelope constrains two variables and holds the rest by convention: a stated suction superheat, a lubricated start, a matched evaporator, and an open discharge path. Selection software carries the two constrained variables, and none of the conventions, and the matrix of modes and signatures is one way to supply what the software leaves out. A detailed safety assessment and a check of the installed system configuration belong before every first start, and plant operators should charge refrigerant under conditions that keep foreign gases out of the system before the first turn-on.

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