



Limitations of Onboard Diagnostics in Domestic Refrigeration Equipment: Why an Error Code Identifies the Symptom Rather Than the Root Cause

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Abstract

Domestic refrigerators increasingly rely on electronic controls that report faults through error codes, and technicians often treat the displayed code as a diagnosis. The research gap is the absence of an analysis explaining, from the standpoint of field repair, what an onboard code can and cannot establish about a sealed refrigeration system. The objective is to determine the diagnostic limits of onboard error codes in domestic refrigeration equipment and to substantiate a procedure that links the code to a root cause. The methodology combines a structured review of 24 peer-reviewed studies, regulatory documents and standards published, a content analysis of diagnostic logic, and a documented case from the author's field practice in Florida. The results show that codes confirm a deviation in a monitored variable but not the failed component, and that published experiments report overlapping signatures for leaks, restrictions, airflow faults and compressor degradation. A four-class code taxonomy and a three-domain verification protocol are proposed. The conclusions will interest service technicians, appliance manufacturers, trainers and repair policy specialists.

Keywords: Domestic Refrigeration, Onboard Diagnostics, Error Codes, Fault Isolation, Sealed Refrigeration System, Filter-Drier Restriction, Hermetic Compressor, Electronic Control, Appliance Repair.

INTRODUCTION

A household refrigerator is one of the few appliances that operates continuously for its entire service life, and a failure affects food safety, energy use and, when the sealed system is opened, refrigerant emissions. Over the past decade the design of this product has changed faster than the way it is serviced. Mechanical thermostats and electromechanical defrost timers have been replaced by control boards that read several thermistors, switch fans, heaters and dampers, and in many models command a variable-speed compressor through an inverter board. When one of the monitored variables leaves its permitted range, the board stores and displays an error code. The code is convenient for the owner and for the dispatcher of a service call, but it is a product of the control logic and not a measurement of the component that has failed.

The scale of the problem is visible in recent statistics and regulatory forecasts. The Global E-waste Monitor 2024 reports that the world generated 62 billion kg of e-waste in 2022, compared with 34 billion kg in 2010, and projects 82 billion kg by 2030, while the documented formal collection

and recycling rate stood at 22.3% in 2022 and is expected to fall to about 20% by 2030 under current trends [1]. Temperature exchange equipment, the category that includes refrigerators, freezers, air conditioners and heat pumps, accounted for 13.3 billion kg of the 2022 total, of which 27% was documented as collected and recycled [1]. In the United States, the Department of Energy adopted new efficiency standards for refrigerators, refrigerator-freezers and freezers in January 2024, with compliance dates of January 31, 2029 and January 31, 2030; the rule is projected to save 5.6 quadrillion Btu over 30 years of shipments, an 11% reduction relative to the case without new standards, and its engineering analysis examined variable-speed compressors and vacuum insulation panels as design options [2]. At the same time, the Environmental Protection Agency restricted new household refrigerators and freezers to refrigerants with a global warming potential of no more than 150 for products manufactured or imported from January 1, 2025 [3]. These two trends point in the same direction: the refrigerator fleet that technicians will service in the second half of the decade will contain more electronics and more hydrocarbon refrigerant systems with small charges, so each

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diagnostic decision will depend on both the control logic and the sealed system.

Access to diagnostic information has not kept pace with this complexity. Pozo Arcos et al. [4] analyzed 150 user manuals from 48 brands of coffee makers, vacuum cleaners, washing machines and refrigerators and found that manuals always help the user detect a fault through a symptom description, sometimes help locate it, and rarely support isolation of the failed component; instead, they tend to prescribe maintenance or a reset. The U.S. Federal Trade Commission reported to Congress that some manufacturers do not release service manuals and limit the availability of diagnostic software [5]. Svensson-Hoglund et al. [6] described a policy environment in the European Union and the United States where legal and market barriers constrain both the supply of and the demand for repair, and where repair services are concentrated with manufacturers. For an independent technician, the error code table is often the only manufacturer document at hand, which increases the temptation to replace the part that the code appears to name.

The research literature on fault detection and diagnosis (FDD) offers methods, but largely for a different setting. Chen et al. [7] classified automated FDD for building HVAC systems into knowledge-based and data-driven approaches and identified limited fault data, simultaneous faults and model interpretability as persistent obstacles. Bi et al. [8] reviewed artificial intelligence applications for HVAC FDD published from 2013 to 2023 and pointed to difficulties in dynamic, time-varying operation and in reaching sufficient diagnostic resolution. Hu and Yuill [9] showed experimentally that when two to four faults act at once, simple subcooling-based charging methods are likely to give unsatisfactory results. In maintenance engineering, the related problem of units that are removed as faulty and later test as serviceable is studied under the name “no fault found”; Singh et al. [10] identified 169 publications on this topic and noted that economic and risk aspects remain underexplored. What is missing is an analysis, grounded in field repair of domestic refrigeration equipment, of the logical limits of the onboard error code and of the evidence a technician needs to move from the code to the root cause.

The aim of this study is to determine the diagnostic limits of onboard error codes in domestic refrigeration equipment and to substantiate a verification procedure that combines electrical measurements, analysis of the electronic control system and refrigerant circuit parameters to identify the root cause of a fault. **The scientific novelty** lies in a classification of onboard error codes of domestic refrigerators by the diagnostic information each class carries, linked to a three-domain verification protocol that specifies which discriminating measurements are needed before a component is replaced. **The author’s hypothesis** is that an onboard error code reliably localizes a deviation to a

monitored variable but not to a component, and that the root cause can be isolated with confidence only when evidence from the electrical, control and refrigerant circuit domains converges on the same explanation.

The study has several limitations that define its scope rather than reduce its usefulness. The field material comes from the practice of one author and is used as a documented illustrative case, not as a statistical sample; the author did not keep systematic records of all repairs, so no rates of repeat visits or replaced parts are reported, and statements about such outcomes are presented as professional observations. The analysis addresses domestic refrigerators and refrigerator-freezers with hermetic compressors and capillary tube expansion; commercial systems and heat pumps are discussed only where published findings transfer. Finally, specific error code tables differ by brand and model, so the classification is formulated at the level of code logic rather than individual codes.

The practical value of the work for the United States lies in the connection between diagnostic accuracy and national policy goals. The phasedown of hydrofluorocarbons under the American Innovation and Manufacturing Act, the Section 608 prohibition on venting and its evacuation and technician certification requirements [11], and the DOE efficiency program [2] all rely on a service workforce that can open, repair and recharge sealed systems correctly and can tell a sensor fault from a refrigerant fault. The author’s professional background matches this need: more than 15 years of diagnosing and repairing household appliances and refrigeration equipment, higher technical education in electrical systems and complexes of transport equipment, EPA Section 608 Universal certification, and since 2022 his own service company in Sarasota County, Florida, which serves homeowners, rental housing, property management companies and home warranty clients. A technician who combines electrical, electronic and sealed-system competence helps extend the service life of installed equipment, avoids unjustified replacement of working components and reduces refrigerant releases, which supports U.S. objectives in energy efficiency, climate policy and waste reduction.

MATERIALS AND METHODS

The study follows a qualitative applied research design that is common in engineering papers written from professional practice. It combines four methods, each assigned to one part of the argument: a structured literature review, a content analysis of regulatory and technical documents, a logical analysis of onboard diagnostic functions, and a documented single-case analysis from the author’s field work. The results of these methods were brought together in an authorial synthesis, which produced the code classification and the verification protocol presented in the Results and Discussion.

The structured literature review covered peer-reviewed journals indexed in Scopus and Web of Science and published by Elsevier, Springer, MDPI and Emerald, supplemented by U.S. federal regulatory documents and industry standards. Searches used combinations of the terms “domestic refrigerator”, “household refrigerator-freezer”, “fault detection and diagnosis”, “capillary tube clogging”, “refrigerant leakage”, “hermetic compressor failure”, “multiple simultaneous faults”, “sensor fault”, “repair” and “no fault found”. The inclusion criteria were a publication, a verifiable bibliographic record with a DOI or an official publication number, and direct relevance to fault signatures, diagnostic logic, refrigerant handling or repair policy. Blogs, press releases, news items and vendor marketing materials were excluded. The final source base contains 24 items.

The source base was grouped into five types according to its role in the analysis. The first group consists of experimental and simulation studies of faults in domestic refrigerators: fan faults, condenser fouling and area restriction [12], capillary tube clogging [13], 3-way valve faults and start-up behavior [14], refrigerant micro-leakage in an R600a refrigerator [15], intelligent control of a refrigerator with a variable-speed compressor [16], and failure analysis of domestic compressors [17]; a review of the adverse effects of compressor lubricant on household refrigerator-freezers [18] belongs to the same group. The second group includes reviews and experiments on FDD methods and their limits [7, 8, 9, 19, 20], work on sensor bias detection [21], and a systematic review of “no fault found” events [10]. The third group covers repair information and repair policy [4-6]. The fourth group contains U.S. regulations and standards: the Section 608 rule revision [11], the Technology Transitions rule [3], the Emissions Reduction and Reclamation rule [22], the DOE efficiency standards [2], the AHRI refrigerant purity standard [23] and the ASHRAE Handbook on refrigeration [24]. The fifth group is statistical: the Global E-waste Monitor 2024 [1]. Manufacturer service manuals, wiring diagrams, error code tables and built-in test mode procedures used by the author in daily work informed the logical analysis but are not cited individually, because they are model-specific and not all of them are publicly available.

The content analysis examined how each document defines or implies a diagnostic step: what is measured, what threshold or rule is applied, and what conclusion is drawn. For regulatory documents, the analysis extracted the requirements that constrain diagnostic practice, such as evacuation before opening an appliance, the prohibition on venting, and purity limits for refrigerant. For experimental studies, the analysis recorded which parameters changed under each fault and whether the authors could distinguish that fault from others using one parameter.

The logical analysis of onboard diagnostics reconstructed, in a brand-neutral form, the rules by which a control board

of a domestic refrigerator generates a code: range checks on sensor circuits, time-based checks on defrost termination or compartment temperature, feedback checks on fans and dampers, and communication checks between boards. For each rule, the analysis asked which physical states of the appliance could produce the same code. The answer was organized as a mapping from code classes to candidate root causes in three domains: electrical (supply, windings, relays, heaters, protectors), control (sensors, board outputs, firmware logic, communication) and refrigerant circuit (charge, restrictions, compressor pumping, heat exchange and airflow).

The field material comes from the author’s practice: since 2007 as the owner of an electronics and electrical equipment service in Ukraine, and since 2022 as the owner of V & P Repair Service Inc. in Florida. Over this period the author has completed thousands of repairs of household appliances and refrigeration equipment, but no systematic statistical sample was kept. For individual complex cases, technical parameters were recorded before and after repair: supply voltage, component resistance, current draw, refrigerant pressures, air and circuit temperatures, error codes and the results of built-in test modes. The instruments used were a digital multimeter, a clamp meter, a refrigerant manifold gauge set, temperature probes and the equipment’s own diagnostic modes. A repair was considered successful when normal operating parameters were restored, error codes did not reappear, the appliance completed a full operating cycle without deviation and the required compartment temperature was reached. All sealed-system work was performed under EPA Section 608 requirements, including refrigerant recovery, evacuation and a prohibition on venting [11].

The single case selected for detailed analysis was chosen because standard diagnostics did not give a clear answer and because the unit had already undergone a sealed-system repair with compressor replacement by another party. The case is reported qualitatively, using the patterns of electrical and refrigerant behavior that the author recorded, and it is interpreted through the mechanisms described in the peer-reviewed literature. It is used to illustrate the reasoning of the protocol, not to estimate its accuracy.

With the design and sources defined, the next section presents the results in the order of the argument: the logic of onboard codes, the published evidence of overlapping fault signatures, the proposed protocol, the case, and the practical consequences for the industry.

RESULTS AND DISCUSSION

An onboard error code is the output of a rule evaluated by the control board on the signals available to it. The board of a domestic refrigerator typically receives resistance values of NTC thermistors in the fresh food compartment, the

freezer and on the evaporator, the state of door switches, and in some designs speed feedback from fans and position feedback from an air damper. The complexity of these rules is growing. Rodríguez-Valderrama et al. [16] built a fuzzy controller for a domestic refrigerator with a variable-speed compressor that used six input variables, three output variables (fan speed, damper opening and compressor frequency) and 144 rules; depending on user habits, it saved from 2.08% to 5.45% energy relative to the factory control, and in one combined scenario consumed 9.7% more energy while keeping more favorable compartment temperatures. A controller of this kind responds to disturbances by changing compressor speed, fan speed and damper position before any threshold is crossed. The consequence for diagnosis is that the code, when it finally appears, reports the moment when compensation was no longer enough, not the moment or the place where the fault began.

Zhang et al. [15] demonstrated this effect for refrigerant micro-leakage in a dual-temperature R600a refrigerator. In their co-simulation, system pressure and the refrigerant mass in the accumulator deviated first, before cabinet temperatures were affected; at a compressor speed of 2000 rpm the critical leakage area was 0.013 mm², and the maximum tolerable leakage reached 67.6%. For smaller leaks, operating the compressor at a critical speed markedly reduced the temperature deviation. A control board that

monitors only compartment temperature will therefore stay silent through a large part of the leak, and when it reports a high temperature, the code will be indistinguishable from the code produced by a failed defrost heater or a stuck damper.

A second limit follows from the sensor itself. A thermistor with a drifted characteristic still produces a resistance within the valid range, so the range check passes and the board acts on a wrong temperature. Ng et al. [21] showed that biases of about 0.5 °C in temperature sensors can be detected only by combining the readings with thermo-physical relations or statistical models of the system, and not from the suspect sensor alone. A household control board has no such redundancy. The author has repeatedly observed in field practice that a sensor with a plausible but inaccurate reading leads to symptoms that resemble a refrigerant problem, which is one reason to check sensor values against an independent reference thermometer before any sealed-system work.

Based on the logic of code generation, the author proposes to classify onboard codes of domestic refrigerators into four classes according to the diagnostic information they carry. The purpose of the classification is practical: it tells the technician what the code has already proved and what remains to be tested. Table 1 summarizes the classes, the typical trigger logic, the scope of what is confirmed and the discriminating checks that close the remaining uncertainty.

Table 1. Classes of onboard error codes in domestic refrigerators by the diagnostic information they carry (compiled by the author based on [4; 15; 16; 21])

Code class	Typical trigger logic	What the code confirms	What remains open	Discriminating checks
A. Circuit integrity	Sensor or heater circuit resistance outside the valid range (open or short circuit)	An electrical condition exists in a defined circuit	Sensor, connector, harness or board input	Resistance at the component and at the board connector; harness continuity against the wiring diagram
B. Performance and timeout	Compartment temperature above a limit for a set time; defrost not terminated within a set time	The appliance did not reach a target within the allowed time	Any cause in the electrical, control or refrigerant circuit domain (Figure 1)	Full three-domain protocol (Figure 2): current, sensor accuracy, pressure trend, frost pattern
C. Actuator feedback	Fan speed signal missing or out of range; damper position not confirmed	The board did not receive the expected feedback from an actuator	Motor, ice or mechanical obstruction, feedback wiring, board output	Voltage at the actuator, free rotation, feedback signal, ice in the air duct
D. Communication and drive	Data exchange lost between main, display or inverter board; inverter reports a start or overcurrent fault	Two electronic modules disagree, or the drive could not run the compressor as commanded	Wiring, connectors, either board, compressor motor or mechanics, supply quality	Board supply voltages, harness continuity, winding resistance, current at start, test mode behavior

The classification shows a gradient of specificity. Class A codes are narrow in scope because they confirm an electrical condition of a defined circuit, yet even here the code names a circuit and not a component: an open thermistor circuit can result from the sensor, a connector, a harness break at a door hinge or a failed input on the board. Class B codes, which include high compartment temperature alarms and defrost duration alarms, are broad, because the rule that triggers them integrates the performance of the entire appliance. Classes C and D fall between them. In the author's field practice, Class B codes lead to premature replacement of a compressor, a control board or a sensor more often than codes of other classes, because the code text points toward the monitored quantity while the root cause lies elsewhere.

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The divergence behind a single Class B code is easier to grasp in graphical form than in a list, because the same alarm connects to causes in all three domains at once. Figure 1 shows the candidate root causes that the author considers when a compartment temperature alarm appears, grouped by domain.

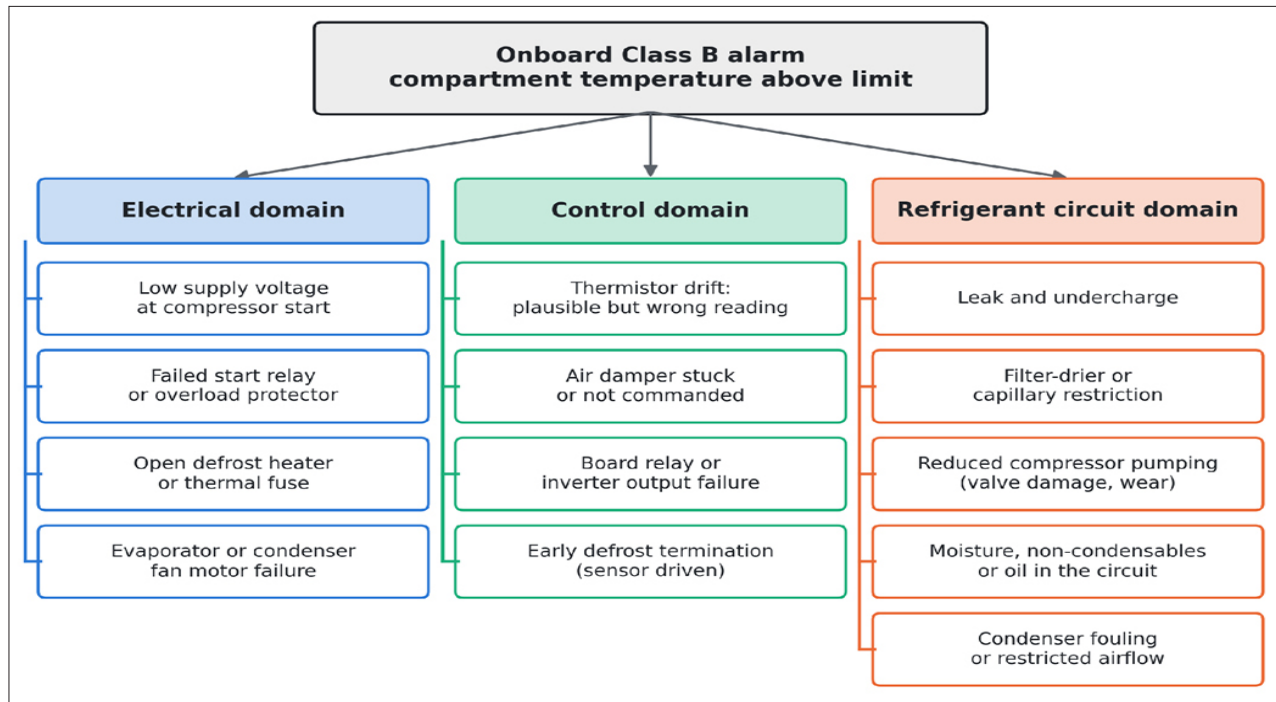


Figure 1. Divergence of candidate root causes behind a single onboard compartment temperature alarm in a domestic refrigerator (compiled by the author based on [12; 13; 16; 17; 21])

Figure 1 makes clear that four or more candidates exist in each domain and that some of them interact. An iced evaporator, for example, is a refrigerant-side symptom caused by an electrical fault (an open defrost heater) or a control fault (a faulty evaporator thermistor that ends defrost early). A diagnosis that stops at the code therefore has to guess among a dozen hypotheses, and the probability of a correct guess depends on the technician's experience rather than on evidence.

The field observation that different faults look alike is supported by controlled experiments. The studies reviewed here were not designed to evaluate onboard codes, but each of them reports how a specific fault changes measurable parameters and whether the fault can be distinguished from others. Table 2 brings these results together to show which conclusions a single parameter supports and where additional evidence is required.

Table 2. Published evidence of overlapping fault signatures in refrigeration systems (compiled by the author based on [12; 13; 14; 15; 17; 18; 19; 20])

Fault studied	Reported signature	Diagnostic implication
Condenser fan degradation, condenser fouling, rear cover area restriction in a domestic refrigerator	Fan fault at high severity: condenser inlet refrigerant temperature up 14.73 °C, discharge pressure up 2.1 bar, energy use up 48%, COP down 26%	High discharge pressure and long run time can be read as overcharge or restriction when airflow is not checked
Capillary tube clogging in a refrigerator-freezer with a dual evaporation circuit	Cooling capacity and power both decline; COP declines; at 84.1% clogging target temperatures cannot be kept	Low power draw with warm compartments resembles undercharge
3-way valve blockage and leakage, capillary clogging (six scenarios)	Compressor power changes immediately in the first 20 min after start-up	Power detects the fault but cannot locate the blockage; a second parameter is required
Refrigerant micro-leakage in a dual-temperature R600a refrigerator	Pressure and accumulator mass deviate before cabinet temperatures; critical leakage area 0.013 mm ² at 2000 rpm; tolerable leakage up to 67.6%	Temperature-based alarms appear late; compressor speed control can mask small leaks
Compressor lubricant circulating in the circuit (review)	Disturbed flashing in the capillary tube, reduced heat transfer, higher compressor work	Oil-related capacity loss imitates restriction or undercharge

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Suction reed valve fracture in compressors of French-door refrigerators	Compressor starts and runs with reduced pumping; causes traced to sharp valve plate edges and misalignment	No start or current code; visible only through pressure difference and capacity
Two to four simultaneous faults in a heat pump in cooling mode	Characteristic fault features shift when faults combine	Simple subcooling-based charging becomes unreliable
Combined charge, airflow, non-condensable gas and liquid line restriction faults in an air conditioner	Capacity reduced by up to 42%, efficiency by up to 39%	A model-based charge diagnostic remained usable; single-feature rules do not
20 simulated fault types in a refrigeration system	Support vector machine accuracy of 95% across system configurations	Reliability depends on how well training data cover the operating regime

Three observations emerge from Table 2. First, the direction of change of a single parameter is often shared by different faults. Pardo-Cely et al. [12] found that a degraded condenser fan raised the refrigerant temperature at the condenser inlet by 14.73 °C and the discharge pressure by 2.1 bar, increased energy consumption by 48% and reduced the coefficient of performance by 26%; a technician who sees high discharge pressure and long run times without checking airflow may conclude that the system is overcharged or that the condenser is restricted. Ko and Jeong [13] showed that capillary tube clogging reduced both cooling capacity and power consumption, and that at 84.1% clogging the compartments could not maintain their target temperatures in any operating mode; low power draw and warm compartments are also the pattern of an undercharged system. Second, a parameter that detects a fault may not locate it. In the start-up study by Ko and Jeong [14], compressor power in the first 20 minutes reacted immediately to six fault scenarios involving 3-way valve blockage, valve leakage and capillary clogging, but the authors could not tell a valve fault from a capillary blockage using power alone and concluded that an additional measurement was required. Third, faults rarely occur one at a time in the field. Hu and Yuill [20] imposed combinations of charge faults, reduced evaporator airflow, non-condensable gas and liquid line restriction on an air conditioner and recorded capacity losses of up to 42% and efficiency losses of up to 39%; a model-based virtual charge sensor performed well under these conditions, while their earlier study showed that simple subcooling-based methods were not reliable when other faults were present [9].

Compressor faults add another layer. Woo et al. [17] investigated failed reciprocating compressors returned from French-door refrigerators and traced the failures to fractured suction reed valves caused by sharp edges on the valve plate and misalignment of components; after design corrections, the modified compressor was expected to reach a B1 life of 10 years. A compressor with a damaged suction valve starts, draws current and runs, so neither a start failure code nor a simple current check reveals it; the loss of pumping capacity appears as a narrowed difference between suction and discharge pressure and as a warm compartment. Ko and Jeong [18] reviewed how compressor lubricant circulating with the refrigerant disturbs flashing in the capillary tube and impairs heat transfer in the heat exchangers, which increases compressor work for the same cooling output. Contamination of this kind links the compressor and the expansion device: after a compressor failure, debris, oil degradation products and moisture can migrate to the filter-drier and the capillary inlet.

Data-driven methods do not remove the problem; they relocate it to the training data. Soltani et al. [19] reported that a support vector machine classified 20 fault types in a simulated refrigeration system with 95% accuracy when validated on data from different system configurations, but they also stressed that reliability depends on how well the training data cover the operating regime. Bi et al. [8] reached a similar conclusion for HVAC in general. Household refrigerators are sold in thousands of variants and operate in kitchens with very different loads, so the onboard controller of a domestic unit is unlikely to carry a classifier of this kind in the near term. The practical implication is that the technician remains the integrator of evidence, and the question is how to structure that integration.

The analysis above leads to a protocol that treats the error code as the entry point of the diagnosis rather than as its result. The protocol was formalized by the author from field practice and aligned with the fault mechanisms reported in the literature. It is organized around three domains, because each domain answers a different question: the electrical domain shows whether components receive and consume energy as designed, the control domain shows whether the board perceives the appliance correctly and issues correct commands, and the refrigerant circuit domain shows whether the sealed system moves heat as designed. The logic is that a hypothesis is accepted only when two or more domains provide consistent evidence for it and the third does not contradict it. A flow diagram is used for this purpose because the sequence and the decision points matter as much as the list of checks. Figure 2 presents the protocol.

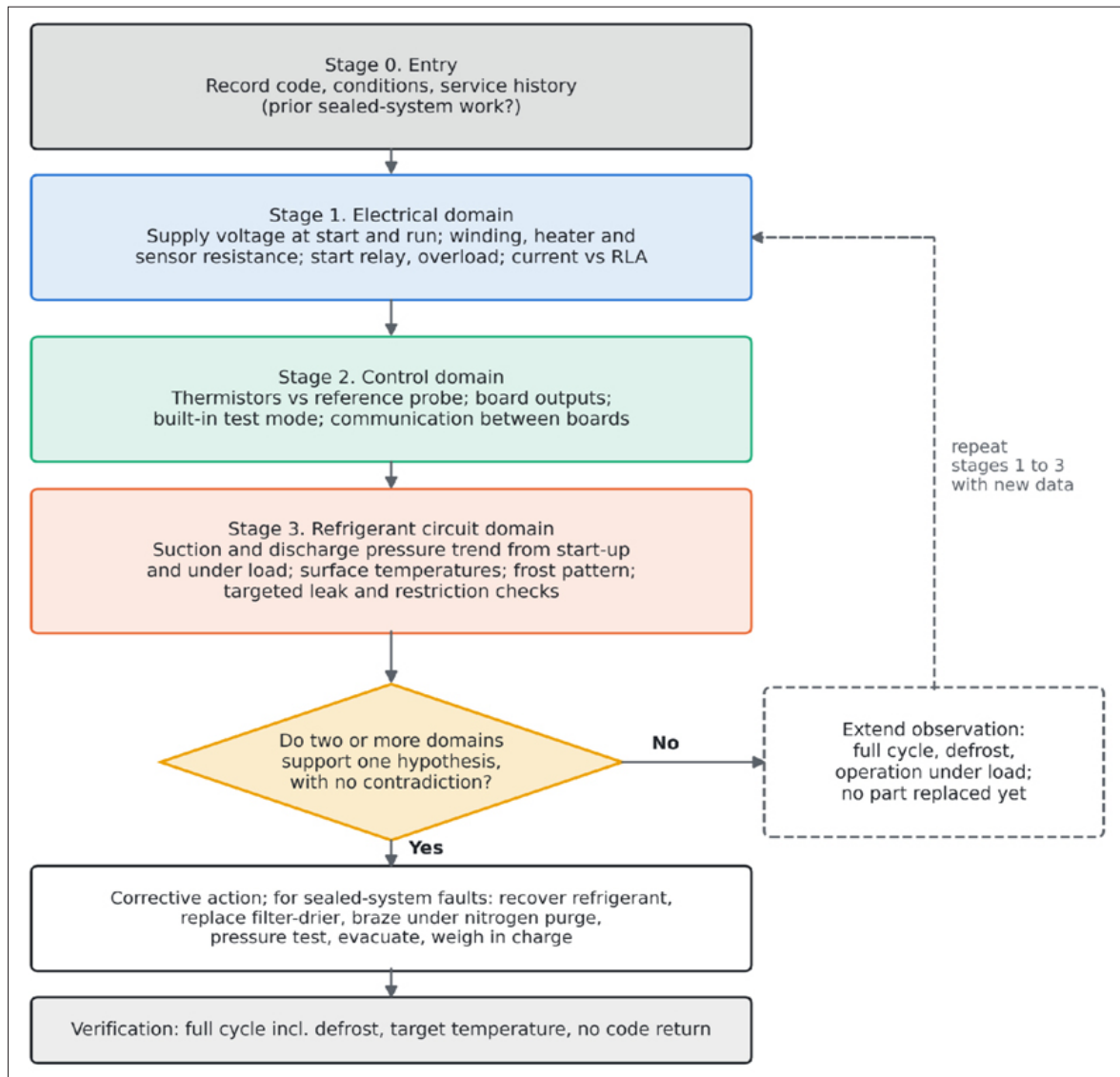


Figure 2. Three-domain verification protocol for code-driven diagnosis of domestic refrigeration equipment (compiled by the author based on [11; 14; 15; 24; 23])

Stage 0 records the code, the conditions under which it appeared and the service history. The service history matters more than it appears: a prior opening of the sealed system changes the prior probabilities of contamination, moisture, incorrect charge and restriction at the filter-drier or capillary inlet, which ASHRAE guidance on contaminant control and system chemistry treats as consequences of improper evacuation and handling [24]. Stage 1 covers the electrical domain: supply voltage at the outlet and at the compressor terminals during start and run, resistance of windings, heaters and sensors against the wiring diagram, condition of the start relay and overload protector, and current draw compared with the nameplate rated load amperes. Stage 2 covers the control domain: comparison of each thermistor reading with an independent probe, verification of board outputs to the compressor or inverter board, fans, heaters and damper; the built-in test mode, and communication between boards. Stage 3 covers the refrigerant circuit: suction and discharge pressure where service access exists or can be created under Section 608 procedures, their change over time from start-up through steady operation, evaporator and condenser surface temperatures, frost pattern on the evaporator, and targeted checks for leaks and restrictions.

Two elements of Stage 3 deserve emphasis. The first is time. A single pressure reading is a snapshot of a system that, in a capillary tube refrigerator, takes many minutes to redistribute refrigerant after start-up; the start-up study by Ko and Jeong [14] and the leakage study by Zhang et al. [15] both show that informative changes occur in the dynamic phase. The author therefore records the pressure trend from start-up and under load rather than a single value. The second is the quality of the refrigerant and of the circuit after any intervention. AHRI Standard 700-2024 specifies purity requirements for refrigerants from any source, including a moisture limit of 10 ppm by weight for R-134a and R-600a and a limit of 1.5% by volume for non-condensable gases [23]. A sealed system that was opened, evacuated inadequately or charged by estimate can operate outside these conditions, and its symptoms will imitate a leak or a restriction.

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The decision gate after Stage 3 applies the convergence rule. If the evidence converges, the technician proceeds to corrective action, which for sealed-system faults includes recovery of refrigerant, replacement of the filter-drier whenever the system is opened, brazing under a nitrogen purge, a pressure test for tightness, evacuation, and a charge weighed to the manufacturer's specification. If the evidence does not converge, the protocol extends observation to a full cycle, including a defrost cycle and operation under load, before any part is replaced. Verification closes the loop: the appliance must complete a full cycle, reach the target temperature and run without the code returning.

The case illustrates how the protocol works when the obvious explanations fail. A household refrigerator was presented after a previous repair of the sealed system that had included compressor replacement by another service provider. The unit did not reach the required temperature. Standard diagnostics did not give an unambiguous answer: the compressor started, the electrical part of the system operated, but the pressure in the refrigerant circuit was unstable. Each of the three conventional single-parameter readings suggested a different conclusion: the warm compartment suggested an insufficient charge, the unstable pressure suggested a leak or a failing compressor, and the running compressor suggested that the electrical and control side was in order. Table 3 records the sequence of checks, the observations and the inferences drawn at each step.

Table 3. Hypothesis elimination record for the documented case (compiled by the author based on field case records and [13; 14; 15; 18])

Step	Domain	Check performed	Observation	Inference
1	Electrical	Supply voltage at the outlet and at the compressor terminals during start and run	Supply adequate; compressor started	Supply fault not supported
2	Electrical	Compressor current at start and in operation; start relay and overload protector	Start components functional; compressor operation unstable	Compressor retained as a possible contributing cause
3	Control	Control outputs, sensor readings, built-in test mode	Compressor and fans commanded as designed	Control or sensor fault not supported as the primary cause
4	Refrigerant circuit	Suction and discharge pressure as single readings	Pressure unstable	Ambiguous: undercharge, restriction and reduced compressor capacity all compatible
5	Refrigerant circuit	Pressure change over time at start-up and under load	Abnormal pressure dynamics consistent with a flow restriction	Restriction retained; undercharge as the sole cause not supported
6	Refrigerant circuit	Targeted check for flow restrictions and leaks	Signs of refrigerant flow restriction in the area of the filter-drier; no finding explaining the symptom as a leak alone	Partial clogging of the filter-drier identified as one cause
7	Synthesis	Convergence of evidence from the three domains	Two concurrent faults: filter-drier restriction and unstable compressor operation	Corrective scope: compressor and filter-drier replacement, nitrogen purge, evacuation, tightness check, charge to specification

The sequence in Table 3 shows why the case resisted a single-parameter diagnosis. The electrical and control checks removed two broad groups of hypotheses but did not explain the symptom. The static pressure readings were compatible with undercharge, restriction and reduced compressor capacity at the same time. Only the time behavior of the pressures at start-up and under load, together with the targeted check of the circuit, pointed to a partial restriction in the area of the filter-drier. The same record also showed unstable operation of the compressor, which meant that the restriction was not the only fault. The partial clogging of the filter-drier made the pressures change abnormally, and this pattern could have been read either as a shortage of refrigerant or as a compressor fault. Had the technician followed the first reading, the likely outcome would have been an added charge or a replacement of the compressor alone, and in both scenarios the other fault would have remained in the system.

The elimination path is easier to follow as a tree of hypotheses in which each branch is closed by a specific piece of evidence. Figure 3 shows this tree for the case, from the initial symptom to the combined conclusion.

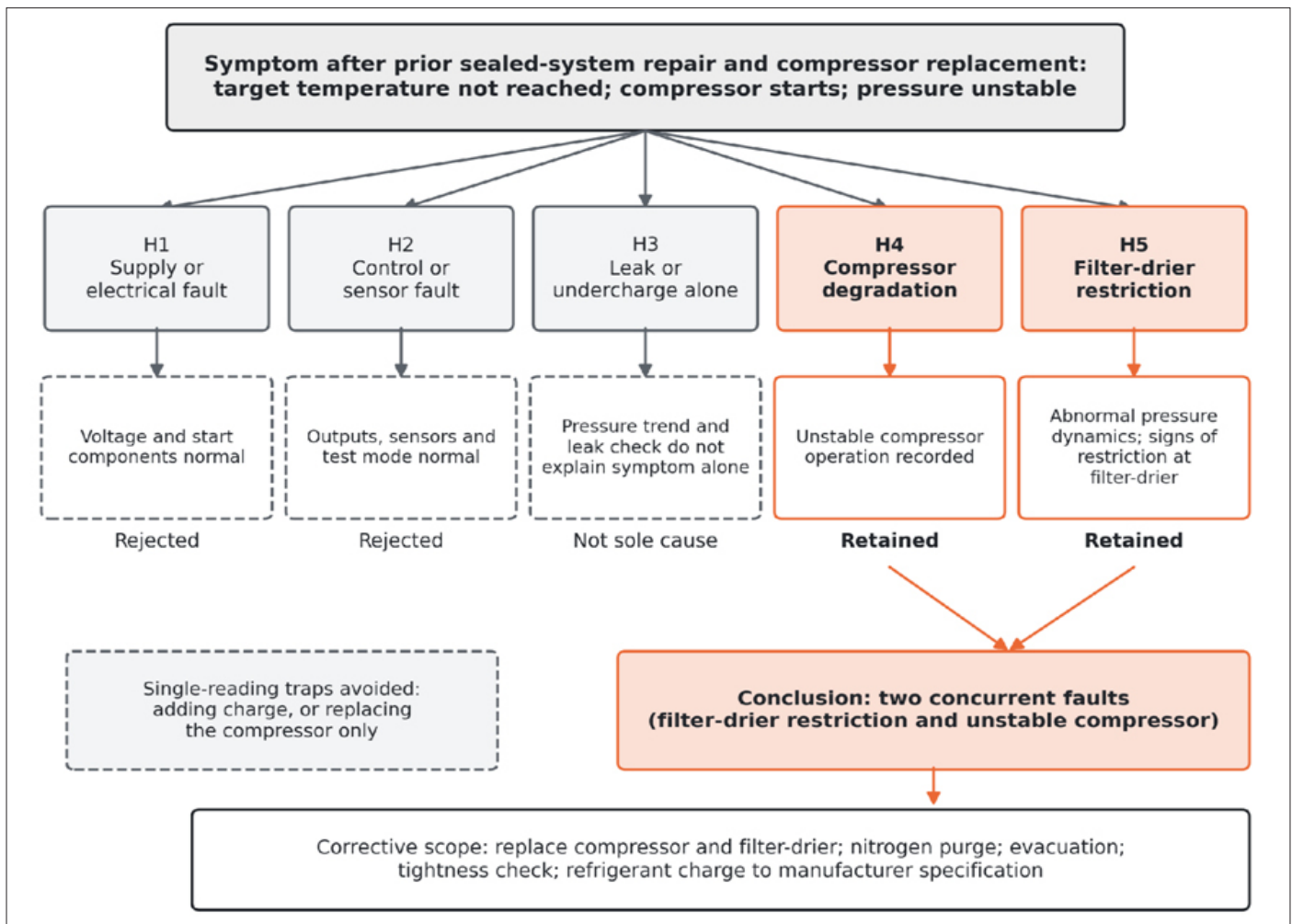


Figure 3. Hypothesis elimination tree for the documented case of unstable operation after a prior sealed-system repair (compiled by the author based on field case records and [13; 18])

The case result agrees with the mechanisms described in Section 3.2. A compressor that failed once can leave debris, degraded oil and moisture in the circuit, and the filter-drier is the first component to collect them; Ko and Jeong [18] describe how lubricant in the circuit disturbs the capillary flow, and Ko and Jeong [13] show how progressive clogging lowers capacity until the compartments no longer reach their targets. A second compressor installed into a contaminated circuit works under abnormal suction conditions, which is consistent with the unstable compressor operation recorded in the case. The corrective scope recommended by the author therefore addressed the system rather than a single part: replacement of the compressor and the filter-drier, flushing and purging of the circuit with dry nitrogen, evacuation, verification of tightness, and an accurate charge of refrigerant according to the manufacturer's specification. The acceptance criteria were those defined in the Methods: restored operating parameters, absence of error codes, a stable complete operating cycle and the required compartment temperature.

The case also shows the limits of what a code could have offered. Even a well-designed Class B alarm would have reported only that the compartment was warm. No onboard signal in a typical domestic refrigerator measures suction pressure, discharge pressure or compressor pumping efficiency, so the two faults that mattered were outside the observable space of the control board. This finding supports the hypothesis stated in the Introduction for this case: the code, and each single physical reading, localized a deviation, while the root cause became visible only when evidence from the three domains was combined.

A misdiagnosis in a domestic refrigerator has consequences beyond the individual service call. Each unnecessary replacement consumes a component, each unnecessary opening of the sealed system is an opportunity for refrigerant loss and contamination, and a repair that fails twice increases the chance that the owner replaces the appliance. The broader waste context is shown in Figure 4, which presents statistical data from the Global E-waste Monitor 2024 on e-waste generation and documented collection, including the category of temperature exchange equipment. A chart is used here because the gap between generation and documented recycling is the quantity of interest.

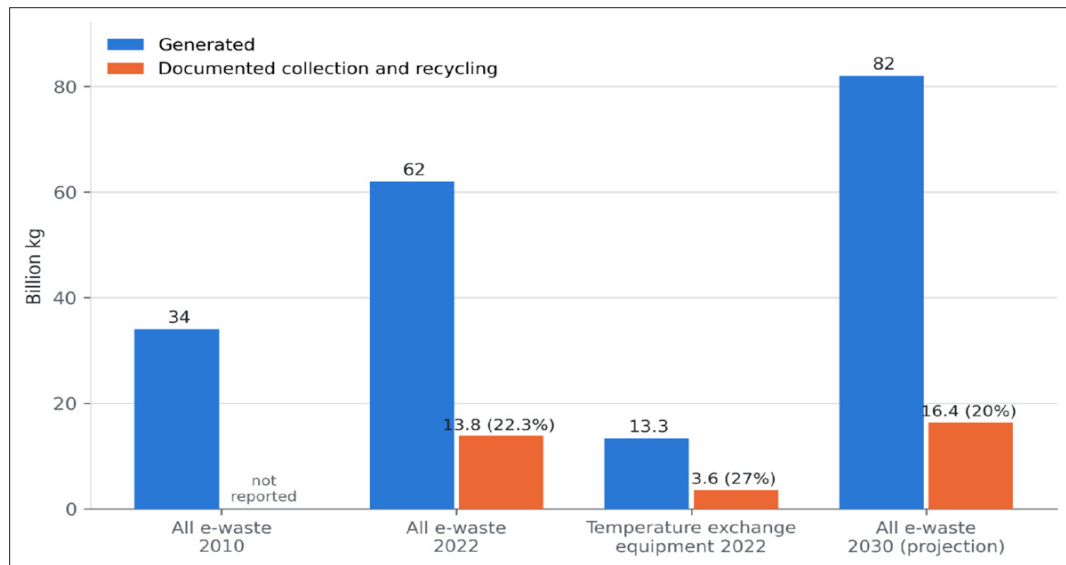


Figure 4. Global e-waste generation and documented collection and recycling, 2010 to 2030, including temperature exchange equipment (compiled by the author based on [1]; recycled volumes calculated by the author from the reported rates)

Figure 4 shows that global e-waste generation grew from 34 billion kg in 2010 to 62 billion kg in 2022 and is projected to reach 82 billion kg in 2030, while documented collection and recycling covered 22.3% of the 2022 amount and is expected to decline to about 20% by 2030 [1]. Temperature exchange equipment, which includes refrigerators, contributed 13.3 billion kg in 2022, of which 27% was documented as collected and recycled [1]. For this category, end-of-life treatment also determines the fate of refrigerants and foam blowing agents. Extending the service life of a working refrigerator by a correct repair is a direct, if modest, contribution to reducing this stream, and a correct diagnosis is the precondition of such a repair.

The regulatory framework places the responsibility for refrigerant handling largely on the technician. Under the 2020 revision of the Section 608 program, substitute refrigerants remain subject to the venting prohibition, technician certification and sales restrictions, evacuation requirements before an appliance is opened, and safe disposal requirements for small appliances [11]. The 2024 Emissions Reduction and Reclamation rule introduced leak repair and reclaimed refrigerant requirements for HFC appliances with charges of 15 pounds or more [22]; household refrigerators, whose charges are far smaller, fall outside those leak repair thresholds. For this equipment, therefore, the quality of sealed-system work depends on the individual technician's discipline rather than on mandated leak inspection. The transition of new household refrigerators to refrigerants with a GWP of 150 or less [3] adds flammable hydrocarbon systems with small charges, in which an unnecessary opening carries both an environmental and a safety cost.

The results allow the author to formulate recommendations for the three groups that shape diagnostic practice: manufacturers, service organizations and technicians, and those who set training and repair policy. The

recommendations follow from the classification in Table 1, the protocol in Figure 2 and the case in Figure 3.

For manufacturers, the author recommends that service documentation present each error code together with its class and a short list of candidate causes in each of the three domains, instead of a single suggested part. The FTC report [5] and the analysis of 150 manuals by Pozo Arcos et al. [4] both indicate that available documentation rarely supports fault isolation, and a code table organized by class would move documentation from detection toward location at low cost. The author further proposes that control boards store, at the moment a Class B code is set, the values of all thermistors, the recent compressor duty cycle or speed profile, and the time since the last completed defrost. This snapshot would let the technician distinguish, for example, a warm compartment with a long compressor duty cycle (pointing to the refrigerant circuit or airflow) from a warm compartment with a short or interrupted duty cycle (pointing to control or electrical causes). The data are already available to the board in many models, so the proposal concerns documentation and firmware rather than new hardware.

For service organizations and technicians, the author recommends a minimum evidence rule: no sealed-system component and no control board should be replaced on the basis of a Class B, C or D code until two or more domains of the protocol support the same hypothesis. In practice this means that every call involving a temperature alarm includes a supply voltage and current check, a comparison of sensor readings with a reference probe, and, where the symptoms point to the sealed system, a pressure trend from start-up rather than a single reading. The service history should be recorded as a diagnostic input, because a previous sealed-system repair changes which hypotheses are likely. When the sealed system is opened, the filter-drier should be replaced and the system evacuated and charged by weight,

in line with Section 608 practice [11] and refrigerant purity requirements [23].

For training and repair policy, the author recommends that preparation of appliance technicians combine refrigerant handling certification with training in electrical measurements and electronic controls, since the case analysis shows that the decisive evidence often lies at the boundary of these fields. Repair policy discussions in the United States and the European Union have focused on access to parts, manuals and diagnostic software [6]; the present analysis suggests that access to the logic behind error codes, and not only to the code tables, is part of what independent technicians need. The same logic could help reduce the “no fault found” returns discussed in maintenance engineering [10], since a component removed on the basis of a code and later found serviceable is a direct cost of symptom-level diagnosis.

The recommendations apply under several conditions. The protocol assumes that the technician has access to the wiring diagram and a basic description of the control logic for the model, and that sealed-system work is performed by a certified technician. For variable-speed compressors, current and speed readings have to be interpreted with the inverter’s operating mode in mind, which the manufacturer’s documentation should describe. For hydrocarbon refrigerant systems, access to pressures may require installing service valves under the manufacturer’s procedure, so the decision to open the circuit should follow, not precede, the electrical and control stages. Within these conditions the protocol adds time to the first visit, but in the author’s field experience this time is repaid by fewer incorrect part orders and fewer return visits; since no systematic statistics were kept, this effect is stated as a professional observation, and its measurement is a task for future work with a structured case registry.

CONCLUSION

The study set out to determine the diagnostic limits of onboard error codes in domestic refrigeration equipment and to substantiate a verification procedure that links a code to a root cause. The analysis of code generation logic showed that a code is the output of a rule applied to the signals available to the control board, and that it confirms a deviation in a monitored variable rather than the failure of a specific component. The proposed four-class taxonomy (circuit integrity, performance and timeout, actuator feedback, and communication and drive codes) describes what each class proves and what remains to be tested; performance and timeout codes, such as compartment temperature alarms, carry little information about the root cause and connect to candidate causes in all three domains.

The review of experimental studies published from 2020 to 2025 confirmed that faults in domestic refrigerators and related systems produce overlapping signatures. Condenser fan faults, capillary tube clogging, refrigerant leakage, valve faults, lubricant effects and compressor valve damage

change the same small set of observable parameters, and a single parameter such as compressor power, subcooling or compartment temperature can detect a fault without locating it. Control strategies that compensate for disturbances delay the moment when a code appears, as shown for micro-leakage in an R600a refrigerator.

The three-domain verification protocol organizes the diagnosis into electrical, control and refrigerant circuit stages with a convergence rule and a verification step. The documented case of unstable operation after a prior sealed-system repair showed how this protocol separated two concurrent faults, a partial restriction at the filter-drier and unstable compressor operation, which single readings would have presented as either an undercharge or a compressor failure. The corrective scope therefore covered the compressor, the filter-drier and the preparation and charging of the circuit to the manufacturer’s specification.

The practical significance of the work lies in recommendations that can be adopted without new hardware: classifying error codes in service documentation, storing a data snapshot when performance codes are set, applying a minimum evidence rule before replacing sealed-system components or control boards, and combining refrigerant certification with electrical and electronic training. These measures support the correct handling of refrigerants under Section 608, the transition to low-GWP household refrigerators and the reduction of e-waste from temperature exchange equipment. Future work will focus on a structured registry of field cases, which would allow the effect of the protocol on repeat visits and replaced components to be measured rather than observed.

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