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**COMBUSTION VENTILATION HAZARDS IN HOUSING -
FAILURE MECHANISMS, IDENTIFICATION TECHNOLOGIES, AND REMEDIAL MEASURES**

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Introduction

This paper describes a field research project undertaken by Canada Mortgage and Housing Corporation with the objective of improving on-site procedures for identifying and remedying problems with vented combustion heating appliances in housing. It describes the design and field testing of the Combustion Ventilation Safety Check (or Safety Check). The Safety Check is intended to be a low-cost procedure that could be accurately and quickly performed by a variety of trades, on a majority of existing houses, and under a wide range of weather conditions. In particular, the Safety Check could be used by contractors during renovation, weatherizing or HVAC installations, as a way of ensuring that the house, as a system, is safe from combustion spillage.

Research Method

Research was conducted in three phases: checklist design, field trials, and remedial measures. As part of the checklist design phase, an exploration of failure mechanisms was undertaken which included discussions with industry personnel, tests on condemned appliances and complaint houses, and the intentional modification of houses and chimneys to simulate problem situations. Five test houses were selected in British Columbia, and subjected to extensive testing in which depressurization apparatus (a door fan) was used to establish the air flow and pressure characteristics for the house under various operating conditions (figure 1). The testing was used to establish the pressure and flow conditions that generated significant spillage, or a reversal of air flow in both furnace and fireplace chimneys. Various identification technologies were evaluated, and the range of potential failures suitable for recognition by a checklist was classified.

In the second phase of research, field trials of the checklists were conducted on a 100 house sample, including 20 houses in each of five locations: Ottawa, British Columbia, Toronto, Manitoba and Prince Edward Island. An effort was made to include housing representative of each region, and especially houses that might be problem prone. All houses in the sample were subjected to a Safety Check, and evaluators recorded results and difficulties.

During the third phase of research, remedial measures were proposed for houses that failed some part of the Safety Check. The proposals were reviewed by project managers, and those measures most essential for safety of occupants, or of special interest, were carried out by field evaluators in conjunction with local building trades. Remedial measures were evaluated by means of a repeat Safety Check, and documented as case studies.

PHASE 1: DESIGN OF THE SAFETY CHECK

The design objective was to develop a test procedure capable of revealing potential for a combustion ventilation failure. Initially some difficulty was encountered in defining a failure, especially for gas-fired furnaces and water heaters. Many authorities contacted during the design stage felt strongly that spillage at start-up, occasional backdrafting, and small cracks in heat exchangers were normal and common events, and did not in themselves represent a threat to health or safety. It was argued that the effect of such events on air quality may be less than what occurs from an unvented gas stove, and that concern should be focused on carbon monoxide production, not spillage of combustion gasses. Continuous monitoring of carbon monoxide levels in the five test houses confirmed that CO is not produced by most furnace and water heaters, even after prolonged spillage or backdrafting.

The precise mechanisms which contribute to CO production are difficult to simulate, because so many factors are involved. CO is a by-product of incomplete combustion, and will occur as a result of a dirty burner, impingement of the flame, poor mixing of combustion air, or oxygen starvation. Backdrafting and spillage can cause oxygen starvation if the combustion gasses are re-ingested by the burner. CO generation through oxygen starvation did not occur in the test houses, however, because when hot combustion gasses spill from a furnace or water heater they quickly rise, due to stack forces, and are replaced by cool fresh air from the floor. Re-ingestion is particularly unlikely in the event of backdrafting, since the high exhaust conditions which provoke a backdraft ensure a direct supply of fresh air, and the rapid removal of combustion products. Only in a very tight room or house is reingestion likely to occur.

For purposes of the checklist design, failure mechanisms which can lead to spillage of combustion gasses have been grouped into seven categories:

1. An imbalance in the household ventilation systems.
2. Leakage around or through the heat exchanger.
3. Blockage of a chimney.
4. Breakage or dislocation of a chimney.
5. Overfiring of an appliance.
6. Design flaws in the chimney.
7. Inadequate protection from down winds.

The Safety Check is designed to identify the potential for failures occurring in a house, and is divided into five parts, each of which can be completed independently, or as part of an integrated, logical procedure. The Safety Check has been summarized on a two-sided form with check-off boxes, and is accompanied by a detailed procedures manual. Equipment requirements are less than \$300, and include a smoke pencil, a sensitive pressure gauge, a propane stove, and a gas detector hand pump. Each component of the Safety Check is briefly described below.

Safety Check Part 1: Inspection

A 20 point inspection of chimneys and appliances is conducted to identify design flaws, maintenance requirements, or other problems that may not be revealed by a performance test. Catastrophic events, such as a sudden chimney blockage, can only be prevented through inspections and maintenance. The potential for wind downdrafting can only be revealed through inspection, since down-hill breezes, or other freak wind conditions, are impossible to simulate during the testing. An inspection is also necessary to establish the validity of guidelines and safety limits used elsewhere in the Safety Check.

Safety Check Part 2: Appliance Backdraft Test

The backdraft test measures the potential for flow reversal in either furnace or DHW heater chimneys due to depressurization by competing exhaust systems. Chimney draft is not measured during the test, since this will vary considerably with winds and temperatures, and was found difficult to measure even under moderate winds. Instead, an assumption is made about what is likely to be the minimum total chimney draft. An inclined manometer is then used to measure the maximum pressure difference that is likely to exist between furnace room and outdoors. Worst case conditions are created by making the house as tight as possible (closing exterior doors and windows, and some interior doorways), and by simultaneously operating all exhaust systems (including exhaust fans, clothes dryers, fireplaces, and in some cases, the furnace blower). Fireplace operation is simulated by a portable propane stove.

Backdrafting is a possibility in a house only if the indoor/outdoor pressure difference exceeds the minimum chimney updraft pressure. Minimum chimney draft occurs when the chimney is cold, and the appliance inoperative. Whether or not such a "cold" backdraft constitutes a hazard will depend upon the ability of the particular appliance to re-establish proper venting when fired. A series of field tests were conducted, in which oil and gas appliances were fired against varying backdraft pressures.

Oil-fired appliances with fan-assisted burners were capable of re-establishing updraft even when backdraft pressures were as high as 25 pascals (one pascal equals 0.004 inches of water). However, the backdraft was odorous while the chimney was cold, and was found to cause backpuffing, sooting, and additional odour problems during the first 10 or 15 seconds of start-up. Cold backdrafting in oil chimneys is primarily a nuisance problem, although the increased soot production, and the freeze-thaw cycles inside the chimney, may eventually cause more serious spillage problems.

Naturally aspirated gas-fired appliances were much less likely to re-establish up-draft, and usually failed to overcome backdraft if the furnace room depressurization exceeded the chimney draft by more than 2 Pa. The depressurization sufficient to reverse flow in a chimney under stand-by conditions was often sufficient to sustain backdrafting throughout a complete operating cycle.

For the purposes of the field trials of the Safety Check, a table was prepared listing the Maximum Allowable Depressurization (MAD) limits for various appliances and chimneys (Table 1). MAD limits define a safe operating range, above which a gas appliance becomes a health hazard due to excess spillage, and above which an oil appliance becomes a problem due to odours or sooty backpuffing. The limits are based on empirical measurements of chimney performance in the test houses, although work is in progress to refine the limits through a computerized model of flue performance. In cases where a house exceeds the MAD limit, fans or fireplaces can be turned off during the test, or a window opened, to determine what constitutes a safe operating condition.

Safety Check Part 3: Heat Exchanger Leakage Test

A test of the furnace heat exchanger is conducted immediately following the backdraft test, with the flue sealed and the furnace cold. Both procedures require the furnace chimney to be plugged. Leakage in the heat exchanger is revealed by pressurizing the furnace with the circulating blower, and checking for air flow out of the combustion chambers on a gas furnace, or out of the inspection port on an oil furnace. The furnace blower is manually switched on, and is used to create a positive pressure around the heat exchanger of approximately 50 to 75 Pa. Even a hole as small as 5 cm² causes a detectable flow of air out the top or bottom ports of the combustion chambers. Air currents are made visible by means of a smoke pencil fitted with an extension hose and penlight. Smoke is squirted into each chamber prior to and during operation of the blower. The heat exchanger must be cold, and gas pilot lights extinguished.

The smoke pencil test of heat exchangers was developed during this project because no suitable test existed for use in the field. A wide variety of techniques were evaluated, but all were rejected either because they ignored leaks in certain portions of the heat exchanger, or because of poor sensitivity. Experiments conducted on the test houses indicated that the most significant failure mechanism in heat exchangers is when the blower forces household air through leaks into the combustion chamber (as opposed to contamination of circulating air by combustion gasses). Air leakage into the chamber can cause flame distortion, sooting, CO production and, if the flow is sufficient to pressurize the combustion chamber, spillage through the dilution air or combustion air inlet openings.

Safety Check Part 4: Appliance Spillage Test

A spillage test is conducted on both the furnace and the water heater by operating both appliances in sequence, under worst case depressurization, and checking for spillage at all likely locations using a smoke pencil or the flame from a butane lighter. If any quantity of spillage continues for more than 15 seconds after start-up, the system fails the test.

Appliances are left operating as the gas meter is clocked, and the percentage over- or under-firing is then calculated. More than 15 per cent over-firing is a failure. A CO detector tube is inserted in the flue connector above the dilution air inlet, and a hand pump is used to sample the flue gasses. A CO reading above 50 ppm is considered a failure.

Safety Check Part 5: Fireplace Backdraft Test

A test is completed to reveal the potential for fireplace backdrafting, following a similar procedure to the furnace backdraft test (Part 2). The fire is extinguished, and the chimney closed, but combustion air inlets are left open. With all exhaust systems in the house operating, including the furnace, a measurement is taken of the depressurization of the fireplace room. This "worst case" depressurization is compared to the MAD limit for fireplaces, which defines the safe operating range for a fireplace operating at low burn. High concentrations of CO in gasses from a wood fire make even slight spillage a hazard. Airtight wood stoves are excluded from this test. If a fireplace fails the test, a nearby window is opened to determine the size of relief opening required.

PHASE 2. FIELD TRIALS

The housing sample was composed of 93 single detached houses, four duplexes and three row houses. A cross-section of ages and styles was included, from new, energy efficient, to pre-1920 Victorian. Approximately half the sample had previously experienced some type of ventilation problem. Sixty-three per cent had gas fired, forced air furnaces. The remainder were oil (27 per cent), gas hydronic (6 per cent), and wood or propane (4 per cent). Seventy-seven per cent had at least one wood fireplace, and 20 per cent had two fireplaces.

Forty-five per cent of the houses required specific maintenance work, with little consistency in the types of problems identified. A majority of problems pertained to furnaces (88 per cent), with gas appliances suffering from a wide variety of problems, and oil furnaces being particularly susceptible to corroded flue connectors, damaged caps, and imbalanced dampers.

Thirty-six per cent of the houses failed the furnace room backdraft test by exceeding the MAD limits. Depressurization levels were accurately read to 0.2 Pa (except under very windy conditions). Average depressurization by mechanical exhaust systems was 3.2 Pa with slightly less than one third falling in the 1 to 2 Pa range (figure 2). When fireplaces were added to the exhaust, the average depressurization rose to 4.5 Pa (figure 3). Seven houses experienced more than 10 pascals of depressurization, four were above 15 Pa, and one house recorded 22.2 Pa.

In 32 houses, the furnace blower operation served to further reduce air pressures in the furnace room. In another 18 houses, the blower served to pressurize the room. The average effect of the blower was to depressurize by 0.24 Pa. The most extreme cases were a room depressurization of 5.4 Pa, and a pressurization of 4.5 Pa.

Only one house failed the heat exchanger leakage test (Part 3). Seventeen houses failed the operating spillage test (Part 4). In 35 houses, depressurization of the fireplace room (Part 5) exceeded the allowable limit of 3.0 Pa. The extent of fireplace room failures is understated because multiple failures occurring in parts 2, 3, and 4 complicated the procedures.

Average time required by field evaluators on site was 1.7 hours. Commentary by the field evaluators indicated a rapid learning curve, and in all cases they were pleased with the final test design.

PHASE 3. EVALUATION OF REMEDIAL MEASURES

The high number of failures prevented the application of remedial measures in every house where a ventilation hazard had been identified. Instead, a series of cautionary labels were used by field evaluators to warn householders about unsafe operating conditions. The labels were self-adhesive, metallic and could be permanently applied to a furnace, fireplace, fan or air inlet as required. The two most common labels were "DO NOT BLOCK OR RESTRICT THIS OPENING" (19 houses), and "PROVIDE ADDITIONAL AIR SUPPLY FROM OUTSIDE WHILE OPERATING THIS FIREPLACE" (25 houses).

Eleven houses were selected for installation of remedial measures. Emphasis was placed on a group of priority measures thought to be especially suitable for demonstration, due to low-cost or wide applicability. The priority measures focused on backdrafting failures, since these were in the majority, and since most other problems could be resolved through conventional repairs to the chimney or appliance.

Forced and Tempered Air Supply System

A fan and duct heater apparatus was designed and constructed as a system for introducing outdoor air into a basement or appliance room. The system proved to be a suitable remedial measure for houses experiencing chimney failure due to competition from a high powered exhaust system. The fan ensured delivery of a precise quantity of make-up air (75 L/s) when needed, without requiring an excessively large opening, and without causing unwanted infiltration. Fan operation was optionally slaved to exhaust fan, furnace, flue temperatures, a switch by the fireplace, or a micro-pressure switch. A proportionally controlled duct heater (5 kW) warmed outdoor air to room temperatures. Equipment cost \$390.

Direct Air Supply for a Clothes Dryer

A direct outdoor air supply was proposed as a means of balancing air exhaust from a dryer, and proved suitable as a low-cost method of keeping an airtight house, or a house with numerous exhaust fans within the MAD limits. The dryer top was weatherstripped and the back and rear panels were taped to seal inlets and major leaks. A plastic dryer hose was connected to the rear panel for direct air supply to the drum. Measurements of air flow inside both the supply and exhaust hoses indicated that the new duct supplied 2/3 of the dryer air requirements.

Fail-Safe Devices for Gas Fired Water Heaters

A fail-safe device was constructed for gas water heaters. These appliances are most susceptible to spillage and backdrafting, and a fail-safe device provides simple low cost protection. A manual re-set snap therm-o-disc (82°C) was mounted on the draft hood and wired in series with the

thermocouple. Spillage gasses around the hood caused the therm-o-disc to shut off the gas valve (including pilot); it would shut down the water heater after about 30 seconds of continuous spillage. The parts for a fail-safe device cost \$23.

Spillage Alarm for Gas Fired Furnaces

An alarm was constructed to warn householders of excess spillage from a furnace. The alarm was prescribed for marginal failures, or for extremely tight houses where spillage is easier to provoke and represents a greater health risk. A double-throw automatic thermo-o-disc (50°C) was wired in series with the house thermostat, connected to a 24 V metallic buzzer, and mounted in front of the dilution air inlet. It shut down the furnace after 10 seconds of spillage, and would continue to buzz for about 35 seconds. The alarm cost \$22 for parts.

Delayed Action Solenoid Valve for Oil Furnaces

Installation of a delayed action solenoid valve on an oil burner delays oil flow for six seconds after start up. The delay permits the burner fan to overcome cold backdraft pressures, and establish proper draft prior to ignition. It was found to effectively eliminate backpuffing, sooting and odour when firing an oil furnace against a cold backdraft. Cost of the valve is \$65.

Balancing Forced Air Distribution Systems

Some houses experience inordinate depressurization because the circulating blower in the furnace is exhausting air into crawl spaces, attics, garages, wall cavities and perimeter rooms. At the same time the blower may draw air close to the furnace, through filter stocks, leaky plenums, and blower compartment doors. Balancing such systems is a multiple stage process that might include sealing the ducts and plenums, installing additional warm air registers or cold air returns, or connecting a fresh air duct to the return air plenum. The application of such measures succeeded in overcoming problems in failure houses, although the work proved to be tedious. The inclined manometer and Safety Check procedures were especially useful in selecting a strategy, and in monitoring progress.

Additional Remedial Measures

In addition to the priority measures, the field application included balancing an air-to-air heat exchanger, sealing a leaky flue connector, installing a passive air supply to a furnace room, installing a relay switch to interlock a stove-top barbecue fan with an oil burner, extending the height of a chimney to improve draft, and straightening a circuitous, poorly designed flue connector.

In all cases the remedial measures succeeded in improving the ventilation systems so that a repeat of the Safety Check either passed the house, or resulted in a fail-safe situation. Choosing the most appropriate remedial measure for a house proved difficult, with many non-technical factors

influencing the choice. Matching the cost of a remedial measure to the risk was especially difficult, since so little is at present understood about the severity of failures identified by the Safety Check.

A lack of suitable alternatives to the open fireplace proved to be the greatest technical difficulty. The conventional solution of glass doors and a direct air supply did not significantly reduce the hazard from fireplace backdrafting at low burn. Most of the preferred solutions for remedying fireplace failures were beyond a reasonable cost. Direct air supply was effective in balancing the fireplace chimney exhaust as a protection for furnaces, especially in cases where an ash clean-out pit offered an easy air supply route.

Conclusions

Performance test procedures have been shown capable of identifying most types of combustion ventilation hazards in most types of housing, and are simple and quick enough to be performed by a variety of trades persons. The use of Maximum Allowable Depressurization limits to define a safe operating range for appliances simplifies backdraft testing, improves accuracy, and eliminates weather variables. However, more work is required to establish these limits for all types of appliances and chimneys. Heat exchanger leakage tests, and spillage tests, are quick and sufficiently sensitive to identify potential hazards, and can be included with backdraft testing without a significant increase in cost or time.

Backdraft failures comprised about a third of the housing sample, and, next to general neglect, represent the most common potential hazard. Depressurization by fireplaces was a major contributing factor, although mechanical exhaust systems and furnace blowers could, on occasion, create a major imbalance. The capacity of the installed exhaust system was as influential as the building tightness in determining backdraft potential.

Remedial measures for failure houses included a surprising variety of options, most of which were found to work effectively. The choice of a particular strategy is often a difficult task, although the results of the Safety Check were sometimes useful in prescribing a remedy. More guidance is required for users of the Safety Check in assessing the degree of risk from various failure mechanisms, and in selecting appropriate measures. At present there is no easy fix for fireplaces failing backdraft tests, and more research is required.

References

Sheltair Scientific Ltd., Residential Chimney Backdraft Checklist: Design and Evaluation, prepared for CMHC, February 1984.

Sheltair Scientific Ltd., Residential Combustion Safety Checklists, prepared for CMHC, Ottawa, Canada, 1984.

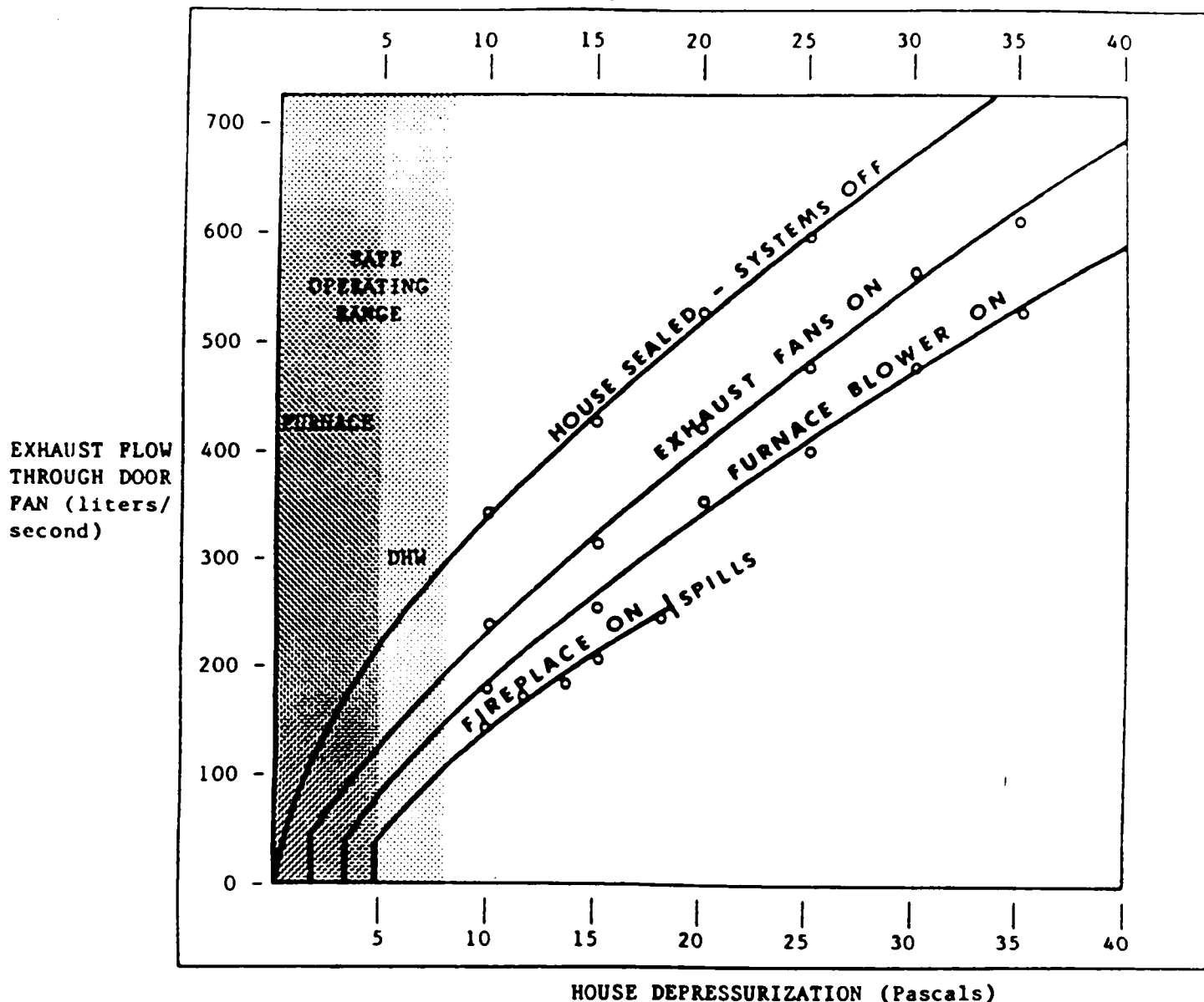


FIGURE 1 A SAMPLE VENT/PRESSURE PROFILE:
Illustrating house pressures, exhaust flows, and chimney
failure pressures for House #36

APPLIANCE	IGNITION	DRAFT	CHIMNEY HEIGHT INLET TO CAP (m)	MAD LIMITS (Pa)
Gas fired DHW	pilot	natural	NA	3.0
Oil fired DHW	electronic	natural	NA	4.0
Gas furnace	pilot	natural	2 - 4	4.0
	pilot	natural	4 - 8	5.0
	electronic	natural	2 - 4	3.0
	electronic	natural	4 - 8	4.0
Oil furnace	electronic	induced	NA	6.0
	electronic	natural	NA	4.0
Wood fireplace	NA	natural	NA	3.0
Gas fireplace	pilot/elec.	natural	NA	3.0

TABLE I MAXIMUM ALLOWABLE DEPRESSURIZATION (MAD) LIMITS
USED DURING FIELD EVALUATIONS OF THE SAFETY CHECK

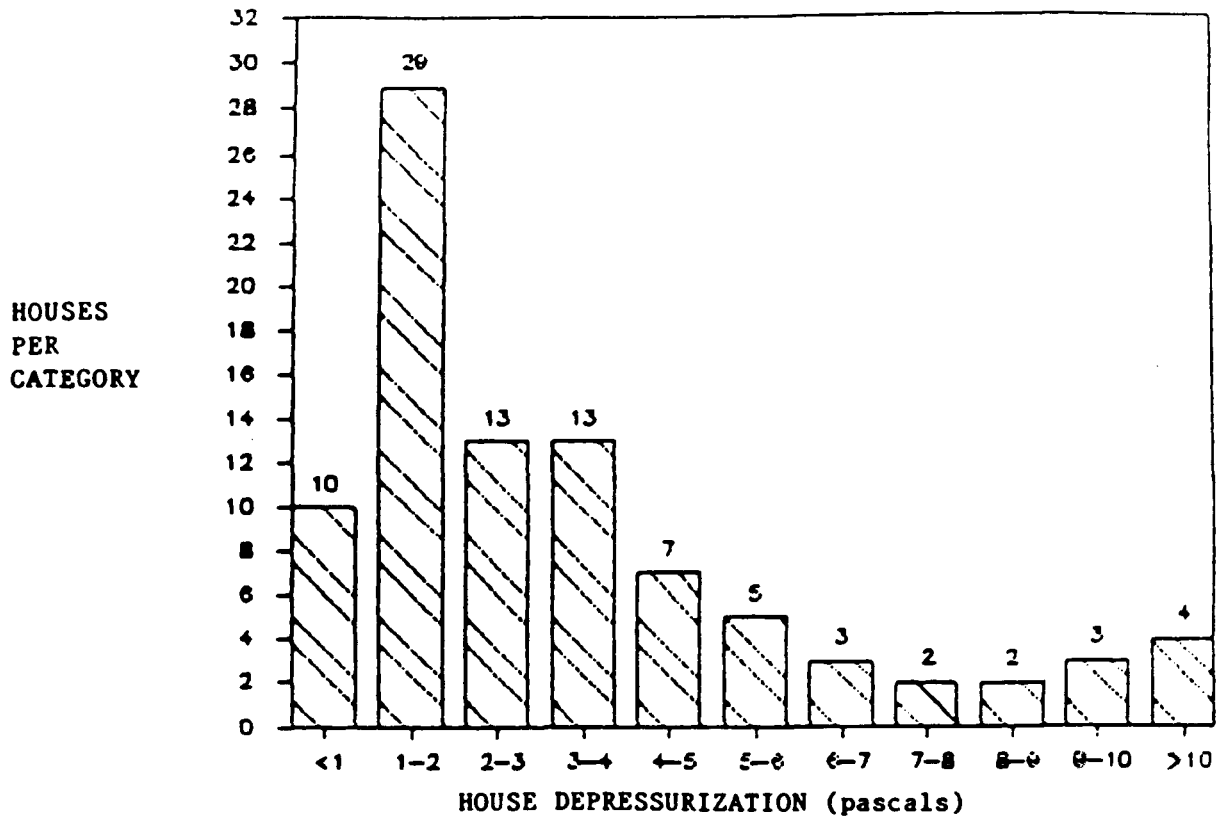


FIGURE 2 DISTRIBUTION OF HOUSE SAMPLE BY DEPRESSURIZATION FROM MECHANICAL EXHAUST DEVICES

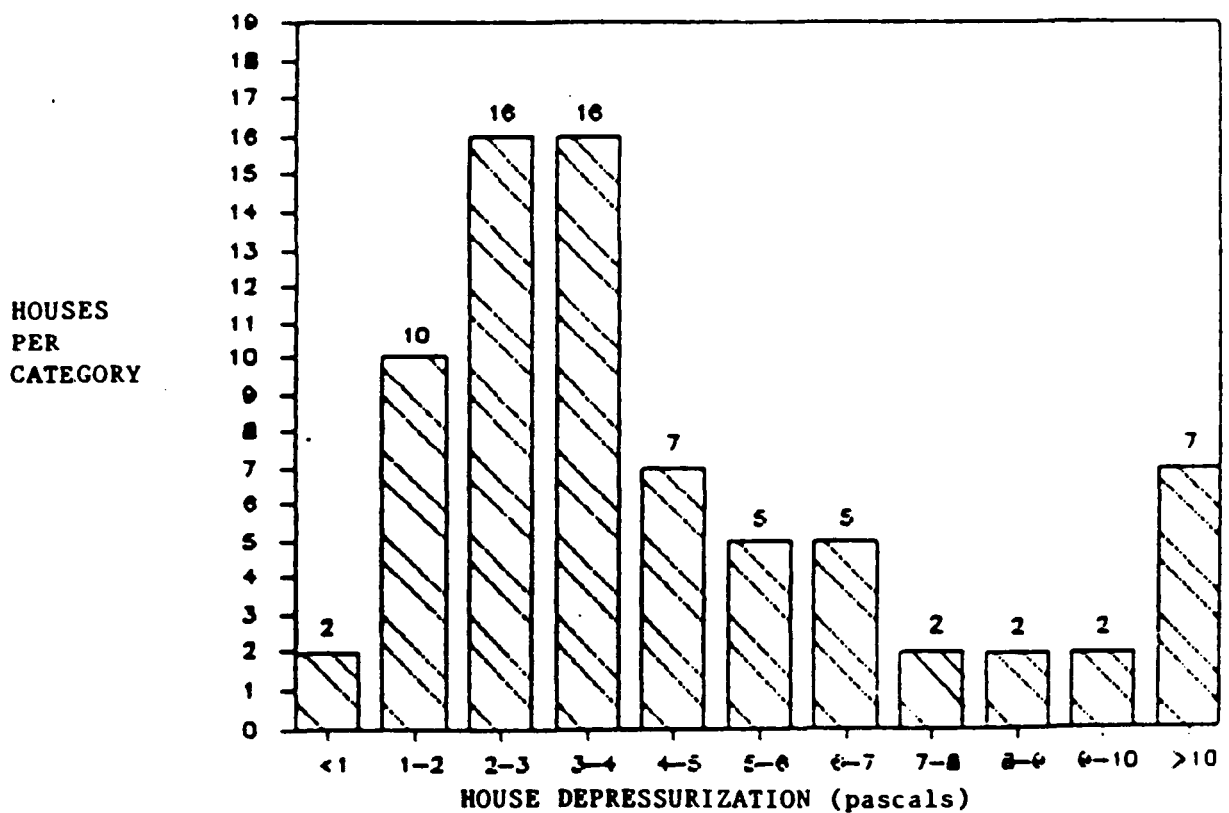


FIGURE 3 DISTRIBUTION OF HOUSE SAMPLE BY DEPRESSURIZATION FROM MECHANICAL EXHAUST DEVICES AND FIREPLACES