There was one major deviation from the construction plan. The roof framing was changed by the contractor to follow local building practices (fig. B-6). The inspection at construction completion revealed a number of hairline cracks, assumed to be from shrinkage, in wallboard corners and basement block joints.

**MONITORING PROGRAM**

A multifaceted monitoring program measured the effects of both natural forces and blasting vibrations on the test house. Bureau personnel installed the monitoring instrumentation at the start of the program and operated the systems at critical periods. At other times, VME (under contract) collected the recordings and shipped them to the Bureau's Twin Cities Research Center for processing. Both Bureau and VME personnel were on-site for the final blasts and mechanical fatigue tests, in addition to an engineer from another company, who was responsible for the mechanical vibrator systems.

**Low-Level Blasting Tests**

During the early phases of the study, static and slowly varying influences were studied. Seasonal weather conditions and effects of settlement and inside environment on static strains and deformations were measured semimonthly at 67 locations within the house. Detailed damage inspections were conducted during the semimonthly testing.

Continuous monitoring of all blasting and weather conditions (both inside and outside environment) was started on October 30, 1979, and continued throughout the study. A Dallas Instruments, Inc., model ST-4 self-triggered seismograph recorded outside vibrations and airblast. Six Rustrak 30-day chart recorders (Gulton Industries, Inc.) monitored temperature, humidity, wind, and, later in the study, two channels of differential displacement (strain). The authors expected that the annual temperature and humidity cycle, as well as daily temperature changes, would introduce cycles of slowly varying stress and consequent strain. They also anticipated that the annual changes (i.e., cross-grain wood shrinkage) would show up in the semimonthly strain measurements. To test for daily variations, a Kaman Sciences Corp. displacement system was used as described later in the "Dynamic Strain" section.

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7Reference to specific products does not imply endorsement by the Bureau of Mines.
The semimonthly evaluations were made for the Bureau by VME, which was required to do the following for each visit:

1. Perform an elevation survey (transit level loop) of the outside of the test house.

2. Change chart recorder tapes each month for--
   Temperature, outside and inside.
   Humidity.
   Wind speed and direction.

3. Change the ST-4 seismograph tapes.

4. Conduct strain measurements utilizing--
   Groove comparator.
   Extensometer.

5. Inspect the structure for cracking; perform mapping and photographing; and note crack lengths and approximate widths.

Periodically during the low-vibration-level phase, dynamic measurements were made of strain and vibration responses, particularly when the mining cycle brought the blasting relatively close to the test house.

The duration of the low-level vibration phase was 16 months, during which the test house was subjected to 645 mining blasts with ground vibrations of <0.75 in/s peak particle velocity. An attempt was made to hold the vibration level of blasts during this period to that level (<0.75 in/s), which is the recommended peak level for Drywall houses (2). Only one shot exceeded this level, by 0.03 in/s, which was within the tolerance of the seismograph's calibration (±10 pct). The house's response to shots 1 to 44 (fig. 5) was recorded during this period.

FIGURE 7. - House relationship to pit (south view).
High-Level Blasting Tests

In March 1981, the mining operation brought the blasting close enough to the house for the vibrations at the test house to exceed 0.75 in/s. Blasting at the working-face area (figs. 7-8) took approximately 1 week to pass by the house during the month-long traverse of the mile-long highwall. During that 1-week period, detailed dynamic measurements and damage inspections were performed. For each blast, strain and vibration time histories were recorded throughout the house (particularly at critical areas near doorways, windows, and corners). At times, as many as 50 FM tape recorder channels were used to record the data.

Structure response and cracking measurements were made periodically over the last 9 months. The house was subjected to approximately 108 blasts >0.5 in/s and one as high as 6.94 in/s. Blasts within 300 to 700 ft and scaled distances of 11 to 30 ft/1b²/2 caused the highest ground vibrations.

Mechanical Vibration Tests

The blasting phase of the study ceased when the highwall had reached to within 300 ft of the test house. Although the house had sustained blast-induced cracking by this time, cracking was hairline (except at one corner of the basement) and structural stability had not been affected. Since major damage had not yet occurred, a decision was made to examine fatigue effects by using mechanical shakers to simulate the effects of repeated loading from mine blasts. While results using short-term continuous cyclic loading would probably not be the same as results from long-term repeated loading from mine blasts, they were nonetheless expected to provide an indication of potential fatigue problems. The house had been subjected to as many blasts as are typically received by a structure near an advancing coal mine. However, cases involving long-term (quarry) blasting indicated that further investigation of cyclic loading was warranted.

Two main study options were considered. The first was relocation of the house and continuation of the blasting tests; the second was accelerated fatigue induced by a mechanical shaker. Relocation was considered impractical because of operational constraints that would have been imposed on the mining cycle, costs, and likely additional damage. The main
FIGURE 9. - Roof joist preparation for mechanical shaker installation.

FIGURE 10. - Installed south-end shaker.
FIGURE 11. - North-end shaker support.

FIGURE 12. - Ceiling joists being bolted to wall studs.
INSTRUMENTATION AND MEASUREMENTS AT TEST HOUSE

A large variety of measurement techniques was needed to quantify strain-producing environmental changes with cyclic periods that ranged from 0.02 s (e.g., blasting) to 1 yr (e.g., seasonal temperature and humidity). Table 4 summarizes the instruments used in the monitoring program. The listed accuracies represent the combined limitations of the instruments and the least division of the chart papers. Locations of all instrumentation are shown in figures 13–16.

FIGURE 13. - Accelerometer and strain system measurement locations on main floor.
FIGURE 19. - Kaman displacement system (top) and 124-mm strain gauge.

FIGURE 20. - LVDT.
Of the 50 FM channels available for recording dynamic data, 27 were usually used for recording strain time histories (16 strain leaf, 9 LVDT, and 2 Kaman). A variety of gauges installed in the master bedroom is shown in figure 22. Before and after the study, a frequency response calibration, from 2 to 100 Hz, was performed on all systems using the Bureau’s 300-lbf shaker system, as described in RI 8506 (29).

Visual Inspection

Crack inspections were conducted throughout the study. During each inspection, crack extension endpoints were marked and the map of cracks at the termination of construction was updated for all crack extensions, nail pops, and new cracks. Two inspectors documented any extensions, new cracks, or nail pops visible to the naked eye, using a trouble light to highlight the visible features. In addition, very detailed inspections were conducted twice each month by VME personnel. They made pre- and post-blast inspections whenever dynamic readings were taken. The time between shots on the same day was sometimes limited, so the inspectors documented material cracking according to an established plan. When vibrations greater than 1.0 in/s were expected, Bureau personnel were also present to document cracking and assist in monitoring.
The results of this study are discussed with the following objectives:

1. To compare strain levels produced by blasting with those induced by natural events.

2. To describe how these natural and manmade events combine to cause cracking in a house.

3. To document the effect of blasting on the crack rate for the test house.

STRUCTURE RESPONSE TO NATURAL PHENOMENA

Insight into the potential of blasting to induce cracking was gained from comparison of strains produced by vibrations and natural events with the strain level at which wallboard failure occurs. The strain level required for wallboard failure was determined from laboratory testing. Previous research and the latest Bureau tests (appendix A) show first cracking of composite wallboard to occur around 1,000 to 1,200 μln/in, regardless of the mode of failure (bending or tension) and rate of loading. Table 6 lists the strains induced in the test house walls in response to various natural (i.e., nonblast) events; for each event, it also lists the corresponding blast vibration level. A detailed discussion of the structure responses to the events listed in table 6 follows.